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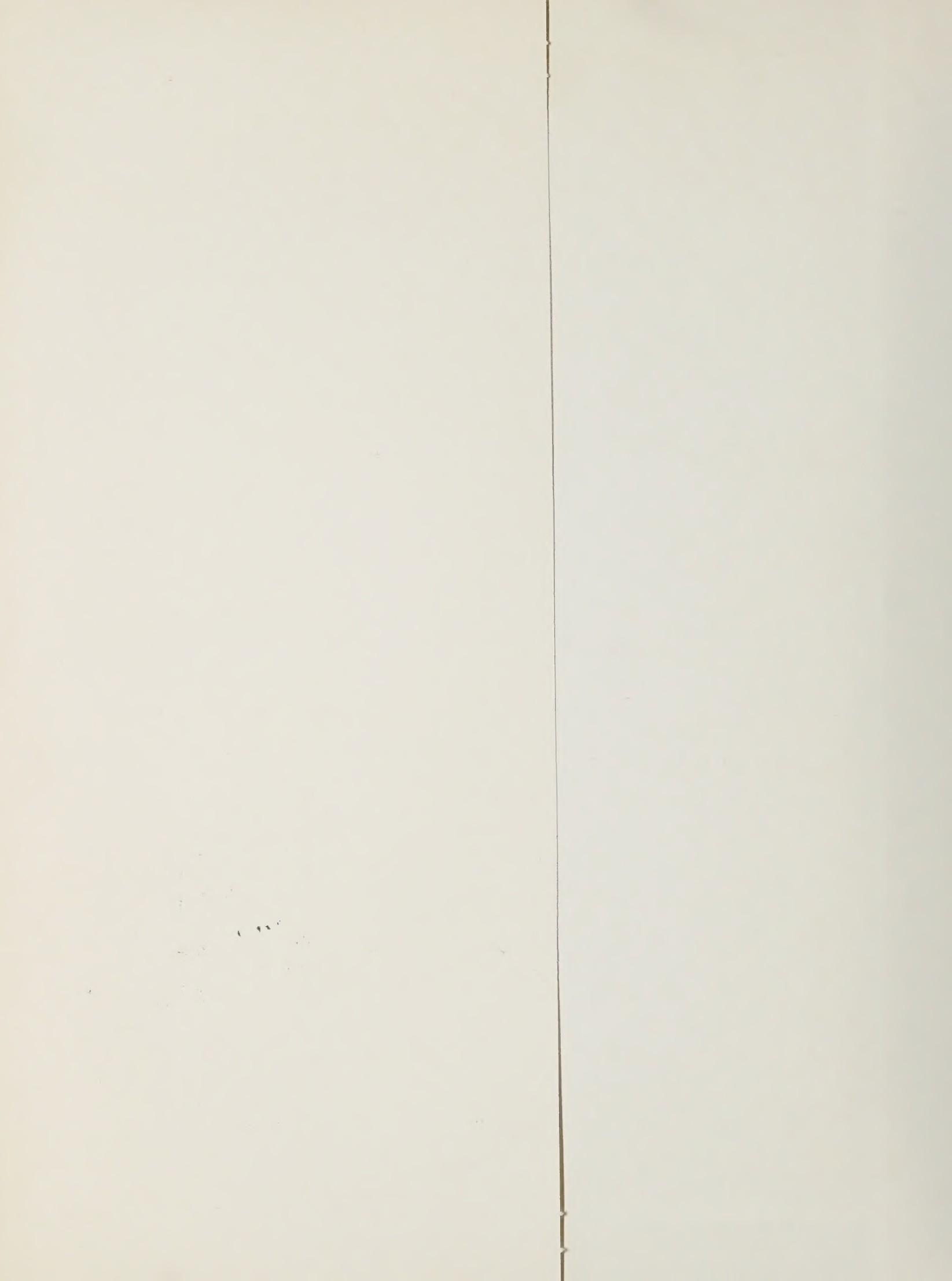
the gravity and magnetic fields of Atlantic offshore Canada

by Richard T. Haworth and J. Brian MacIntyre
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A joint publication of the
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Published by



Environment
Canada

Fisheries and
Marine Service

Publié par

Environnement
Canada

Service des pêches
et des sciences de la mer

Office of the Editor *Bureau du Rédacteur*
116 Lisgar, Ottawa K1A 0H3

CA 1 MT46

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Autres pays: \$3.60

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Ottawa 1975

This report is issued as a joint publication of the Department of the Environment
and the Department of Energy, Mines and Resources in order to serve a wider public.
It may be cited:

-Haworth, R. T., and J. B. MacIntyre. 1975.
The Gravity and Magnetic Fields of Atlantic
Offshore Canada. Marine Science Paper 16. 22 p.
(Also Geological Survey of Canada Paper 75-9)

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THE GRAVITY AND MAGNETIC FIELDS OF ATLANTIC OFFSHORE CANADA

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ABSTRACT

Gravity and magnetic field data collected along approximately 150,000 km of closely spaced ship's tracks off the Atlantic coast of Canada have been compiled at a scale of 1:1,000,000 and set against a background of data collected on a more regional scale. The maps reflect two major flexed lineations. In the west, the Appalachian front is flexed from Gaspé through the Gulf of St. Lawrence to western Newfoundland. In the east, geophysical trends across the Avalon Platform of Newfoundland are shown to be part of major flexed lineations extending from the Northeast Newfoundland Shelf towards the southern edge of the Grand Banks. The flexures possibly result from Paleozoic continental collision. Gravity anomalies on the Grand Banks define the limit of continental crust, and suggest extensive subsidence of that crust northeast of Newfoundland.

RÉSUMÉ

Les auteurs ont compilé, à échelle de 1:1,000,000, les données sur les champs gravitationnel et magnétique recueillies sur environ 150,000 km de parcours rapprochés de navires au large de la côte canadienne de l'Atlantique, et les ont comparées à des données de fond recueillies à échelle plus régionale. Les cartes révèlent la présence de deux flexures majeures des lignes. A l'ouest, le front appalachien présente une flexure à partir de Gaspé, à travers le golfe Saint-Laurent, jusqu'à l'ouest de Terre-Neuve. À l'est, les tendances géophysiques traversant la plate-forme d'Avalon de Terre-Neuve s'avèrent partie de flexures majeures qui vont du nord-est du plateau terre-neuvien à l'accord méridionale des Grands bancs. Les flexures sont probablement le résultat d'une collision continentale. Des anomalies gravitationnelles sur les Grands bancs définissent la limite de la croûte continentale et suggèrent un effondrement important de cette croûte au nord-est de Terre-Neuve.

INTRODUCTION

The Canadian Hydrographic Service and the Atlantic Geoscience Centre have been cooperating in routine geophysical surveys of the Atlantic seaboard of Canada since 1964 (Melanson and Ewing 1970; Macnab 1973). The recent compilation of all the data collected by those surveys has produced a set of detailed 1:250,000 gravity and magnetic maps published in the Natural Resource Series (Canadian Hydrographic Service 1974). In order to interpret specific anomalies defined by those maps, a regional description of the gravity and magnetic fields is necessary. The maps at a scale of 1:1,000,000 accompanying this report attempt to fulfill that requirement by placing the detailed data against a background of both published and unpublished data. Details of the compilation methods used are presented so that intelligent use may be made of the maps.

For convenience, the maps have been made compatible in area, scale, and projection with a series of regional marine

geomorphic maps of eastern offshore Canada (Canadian Hydrographic Service 1969, 1970). For more extensive coverage of the Gulf of St. Lawrence, reference should be made to a companion report (Haworth and MacIntyre 1975).

DATA SOURCES AND COMPILATION TECHNIQUES

There are two main data sources: the published and unpublished data of the Bedford Institute of Oceanography (BIO), and the published data of other institutions. These data are treated in three distinct ways, discussed separately under the following headings:

- 1) *Detailed Survey Data from BIO* compiled in the form of Natural Resource Series maps have been copied directly onto this compilation.
- 2) *Published Contour Maps of Data from Other Institutions* which do not overlap the detailed BIO data have been copied directly onto this compilation.

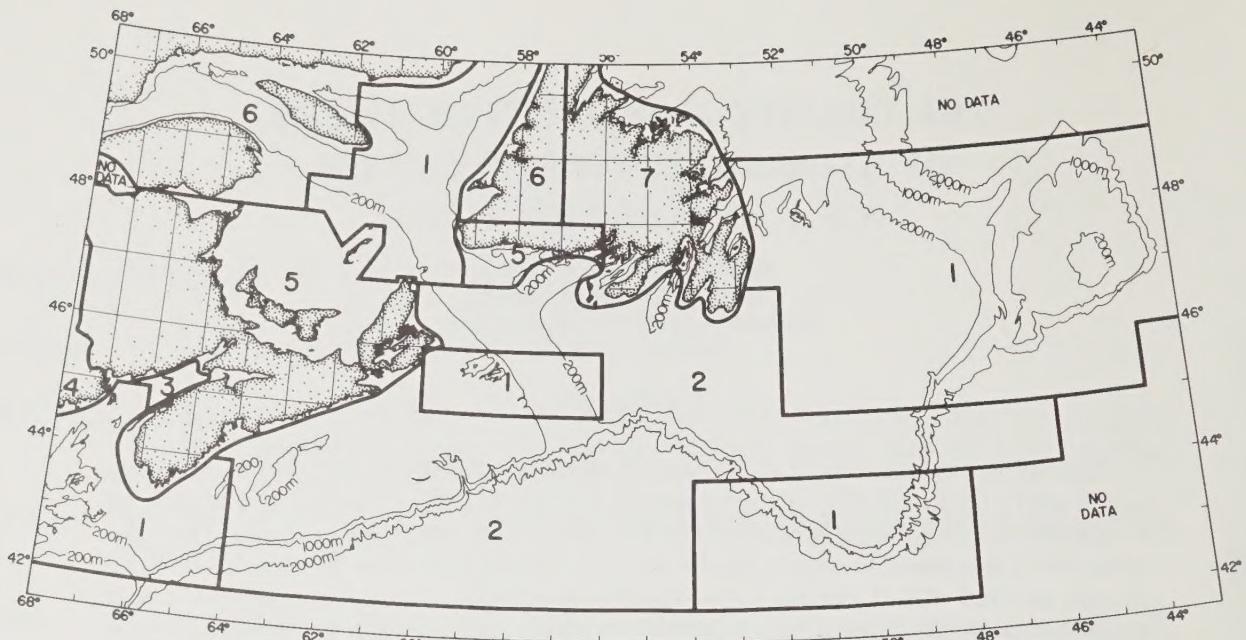


FIG. 1. Sources of gravity data. 1, Atlantic Geoscience Centre (AGC) data from which 1:250,000 Natural Resource Series maps were produced; 2, AGC and Earth Physics Branch (EPB) data averaged over 25-km grid; 3, AGC data, hand-contoured; 4, U.S. Geological Survey data, Kane et al. 1972a; 5, EPB data, Stephens and Cooper 1973; 6, EPB data, Goodacre et al. 1969; 7, EPB data, Weaver 1968.

3) *Sparse BIO and Other Data* have been combined where possible and averaged to provide a regional definition of the potential fields.

In practice the divisions are not quite so definite, but the complexities will become apparent as each category is dealt with. The distribution of source material is shown in Fig. 1 and 2.

1) DETAILED SURVEY DATA FROM BIO

The detailed survey data used in this compilation have been collected during the routine hydrographic-geophysical surveys carried out by the Canadian Hydrographic Service (CHS) with the geophysical support of the Atlantic Geoscience Centre (AGC) (Melanson and Ewing 1970; Macnab 1973). Approximately 150,000 km of track have been surveyed for bathymetric, magnetic, and gravity data since 1964 (Fig. 3). Seismic reflection profiling has recently been integrated with the other operations on selected survey lines. The areas of detailed survey can broadly be classified as Bay of Fundy-Gulf of Maine, the Gulf of St. Lawrence, and the Grand Banks, with a less detailed survey of the Orpheus Anomaly (Fig. 3). Each of these survey operations will be described separately.

Bay of Fundy-Gulf of Maine (Area 1, Fig. 3)—The first geophysical data obtained during CHS surveys were collected in the vicinity of Grand Manan Island in the Bay of Fundy in 1964 (cruise *Baffin* 64-019). This was the first attempt to see whether the survey requirements of geophysical parameters (particularly gravity) could be reconciled with the hydrographic survey standing orders. Simultaneously an attempt was made to collect more detailed magnetic field data using a ship-based helicopter. This was unsuccessful because of difficulties with positioning the helicopter relative to the survey ship. However, the $\frac{1}{2}$ -mile spaced lines oriented N-S

provided very dense coverage of the outer reaches of the Bay of Fundy (Fig. 3). Since on N-S lines the Eötvös correction to the gravity data is extremely sensitive to heading (approximately 1 mgal correction for 1° error in heading on that survey), the gravity data tended to be of a lower quality than is now routine. However, the superfluity of the data compensated for this, giving an accurate picture of the gravity field.

Geophysical coverage was extended into the Gulf of Maine on cruise *Hudson* 71-017 (King 1971; Watts and Haworth 1974). The survey lines were oriented either E-W or NW-SE (perpendicular to the shelf edge). A single zigzag track also provided sparse coverage of the Bay of Fundy. On most lines seismic reflection profiling was also carried out. The survey was carried out without the stringent navigational control of the CHS surveys. This reduced the accuracy of the data as judged from comparison of data at track intersections. However, the greatest problem with gravity data resulted from a series of tares (discrete jumps in the gravimeter reading) in the Askania sea gravimeter Gss 2-17. Analysis of crossover discrepancies isolated the times and magnitudes of the tares (Watts and Haworth 1974) and appropriate corrections were made to the original data. The corrections were vindicated by additional underwater gravity measurements made at cruise 71-014 track intersections during cruise *Sackville* 73-032 (Haworth 1973; Parrott 1974).

Additional control data were provided by isolated lines from cruises *Baffin* 70-002 and *Hudson* 65-034 (Loncarevic 1965b).

Gulf of St. Lawrence (Area 5, Fig. 3)—The hydrographic-geophysical surveys of 1968 and 1969 (cruise *Baffin* 68-021; DeGrasse 1968; cruise *Baffin* 69-021; DeGrasse 1969) covered

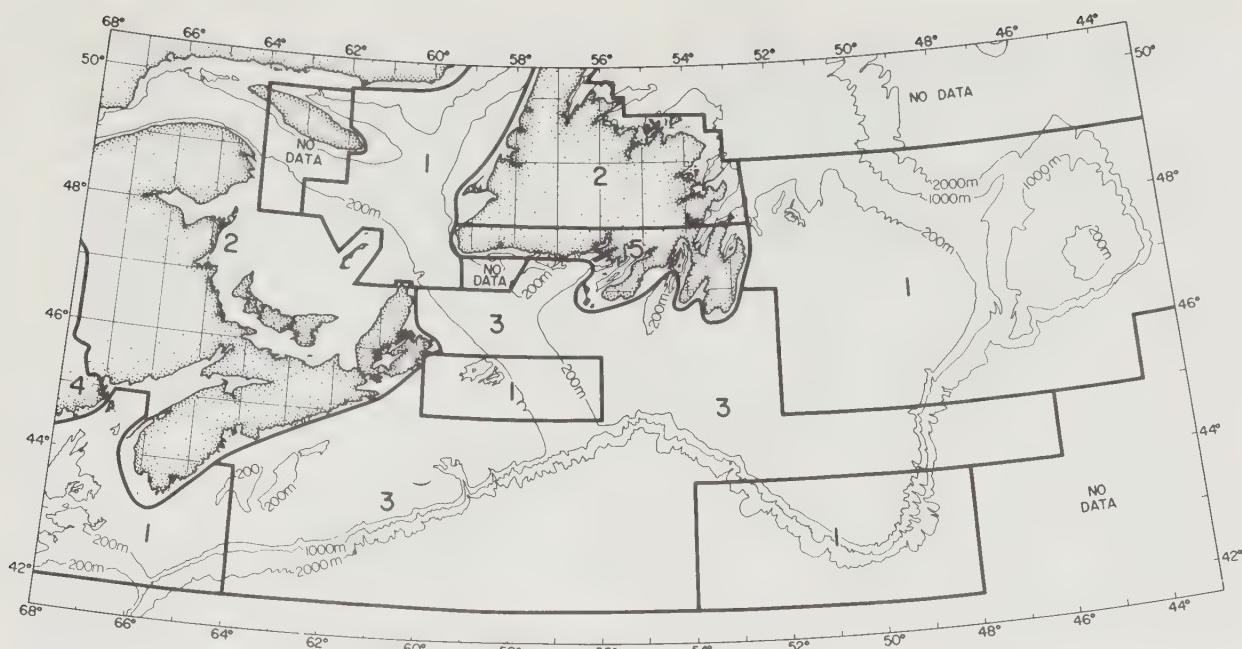


FIG. 2. Sources of magnetic field data. 1, Atlantic Geoscience Centre (AGC) data from which 1:250,000 Natural Resource Series maps were produced; 2, Geological Survey of Canada (GSC) magnetic anomaly map of Canada (1971) and GSC unpublished data, Hood et al. 1974; 3, AGC data averaged over 25-km grid; 4, U.S. Geological Survey data, Kane et al. 1972b.

the eastern portion of the Gulf of St. Lawrence. The variation in line spacing of the surveys (Fig. 3) is dependent upon the water depth. Line spacing is reduced in shallow areas to increase the probability of locating shoals. A minimum depth is set for the survey for the safety of the survey vessel. Around the Magdalen Islands, the inshore limiting depth was approximately 100 m due to dangers from the abrupt changes in bathymetry and because earlier surveys had covered the coastal areas. Dense data coverage (0.9-km line spacing) was obtained on the Magdalen Shelf, the Newfoundland shelf adjacent to Port au Port Peninsula and the northwest edge of the Esquiman Channel (Fig. 4). The greater part of the 1968 survey in the northeastern Gulf was carried out with a 1.8-km line spacing. To the south, a 3.7-km line spacing predominated in the 1969 survey. In the vicinity of Cabot Strait, hydrographic surveys had been completed earlier, and lines separated by 7.4 km were considered sufficient to extend regional geophysical coverage through the Strait. Isolated lines north of Anticosti Island (cruise *Baffin* 68-021), through Cabot Strait (cruise *Baffin* 68-018), and from the northwestern tip of Prince Edward Island (cruise *Hudson* 65-024) are also included in the compilation.

Grand Banks of Newfoundland (Areas 3 and 4, Fig. 3)—The Tail of the Banks (Area 3, Fig. 3) was surveyed in 1966 (cruise *Baffin* 66-008; Smith 1966) with a line spacing of approximately 9 km. The gap in detailed survey coverage between Area 3 and Area 4 (Fig. 3) is due to the commitment of the gravimeter elsewhere at that time and to the breakdown of the magnetometer during the second half of the 1966 survey season. Further coverage of this area has now been completed (cruise *Dawson* 73-034). In 1967, the surveys began coverage of Area 4 (cruise *Baffin* 67-014; DeGrasse 1967). Subsequent surveys in 1971 (cruise *Baffin* 71-017; Dunbrack 1971) and

1972 (cruise *Minna* 72-015; LeLievre 1972) have completed coverage of the Grand Banks to 49°N and have been extended seaward to cover Flemish Cap and the continental slope. The western edge of these recent detailed surveys (along a line bearing 150° from Avalon Peninsula (Fig. 3)) is the eastern limit of earlier hydrographic surveys during which no geophysical data were collected. Geophysical coverage of the Grand Banks south of Newfoundland is therefore limited to that obtained on reconnaissance surveys (King 1972) and transit lines. Shoal surveys in the vicinity of Virgin Rocks and Eastern Shoals account for the extremely dense coverage at 46½°N towards the western edge of the survey area. Coverage of the northern portion of the Grand Banks was completed at 1.8-km spacing, increasing to 9-km spacing over the margin and outer portion of Flemish Cap. Shallow seismic reflection data were collected on selected lines over Flemish Cap.

Orpheus Anomaly (Area 2, Fig. 3)—The Orpheus Anomaly (Loncarevic 1965c; Ewing and Hobson 1966; Loncarevic and Ewing 1967; King and MacLean 1970), extending east from Chedabucto Bay, N.S., has not been subjected to a single rigorous survey. However, data from the original Orpheus cruise (cruise *Baffin* 64-018; Loncarevic 1964) have been supplemented with enough data from several other cruises to permit preparation of 1:250,000 Natural Resource Series maps. Data have been contributed by cruises *Hudson* 65-006 (Loncarevic 1965a; Williams et al. 1972), *Hudson* 66-019 (Loncarevic 1966), *Hudson* 68-022, *Baffin* 71-017 (Dunbrack 1971), and *Hudson* 71-032 (Ross 1971).

Data from cruise *Hudson* 64-027 (Haworth and Barrett 1972) covering the eastern extension of the Orpheus Anomaly from 56.2°W to 58.2°W were not available when preparation of the 1:250,000 maps was begun. They are therefore not included in this compilation.

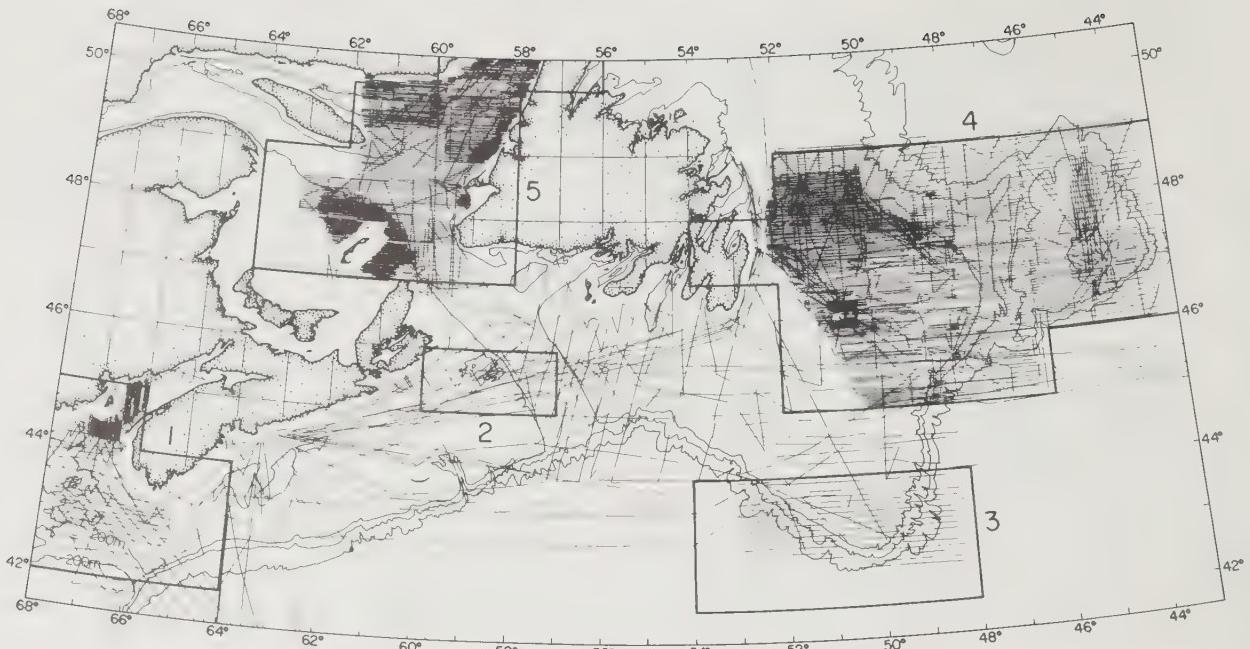


FIG. 3. Bedford Institute of Oceanography ship's tracks along which the gravity and magnetic field data used in this compilation were collected. Areas for which 1:250,000 Natural Resource Series maps are available are outlined by bold lines. Numbers adjacent to the areas are for reference purposes in the text.

Data collection and compilation — Throughout the areas covered by the detailed surveys, gravity and magnetic data were collected continuously and processed to the form of free air and Bouguer gravity anomalies, magnetic total field and magnetic anomaly.

The gravity data were collected using a Graf Askania Gss-2 sea gravimeter mounted on an Anschutz gyrostabilized platform. The filtered electrical output from the meter was applied to a voltage-controlled oscillator whose output was counted for 50 s/min and the resulting digital value was automatically recorded. The digital values were processed to convert them to gravity values in conventional units and to remove the effect of the powerful mechanical damping and electrical filtering to which the meter output is subject (Haworth and Loncarevic 1974). In most cases the final data consisted of single values at 2-min intervals, corresponding to a spacing of 0.7 km at normal survey speeds of 20 km/h.

The total magnetic field data were collected with a proton precession magnetometer towed approximately 200 m astern of the survey vessel. The direct digital readout of the magnetometer in gamma ($1 \text{ gamma} = 1 \text{ nanotesla} = 10^{-9} \text{ weber/m}^2$) was recorded in most cases at $\frac{1}{10}$ -min intervals, but as with the gravity data the final magnetic data were processed at 2-min intervals. Magnetic anomalies were calculated with respect to the International Geomagnetic Reference Field (IGRF) (Cain and Cain 1968; IAGA 1969). During most of the surveys, monitor stations were set up to record magnetic storms and diurnal variations of the magnetic field in the vicinity of the survey area. Such a station has been operated at BIO in Dartmouth, N.S., during all field operations since 1967. Stations were also manned around the Gulf of St. Lawrence during the 1968 and 1969 *Baffin* surveys.

The diurnal variations at each of these monitor stations were compared (Srivastava 1971), and an attempt was made to correlate them with the magnetic variations observed in the survey area. Correcting the magnetic field data from the survey area by linear interpolation between the magnetic variations observed at the Gulf monitor stations gave no significant improvement over directly applying the Dartmouth variations as a correction without changing their phase or amplitude (Srivastava, Atlantic Geoscience Centre, personal communication). With that justification, the magnetic field data for all surveys except *Baffin* 71-017 and *Minna* 72-015 were corrected using the variations as monitored at Dartmouth. When monitor data were not available the shipboard data were either left uncorrected or deleted, depending upon how well they tied with other data in the vicinity. For cruises *Baffin* 71-017 and *Minna* 72-015 on the Grand Banks, monitor data from St. John's, Nfld., were used.

The digital gravity and magnetic data thus collected were the subject of a data processing contract issued in 1972 to Computer Data Processors (C.D.P., now Digitech Ltd.). The methods used by C.D.P. in compiling the data and preparing maps from them have been described elsewhere (Haworth 1974a). Basically, a regular grid of values was created from the data, using an inverse square distance weighting method, and the grid values were contoured, using a hyperbolic asymptote routine. Errors in the basic data set were revealed and corrected during preparation of the grid and contouring. The final corrected file of data was used as the basis for preparation of draft Natural Resource maps of free air gravity anomaly and total magnetic field wherever the line density was sufficient to permit accurate mapping at the publication scale of 1:250,000. The contract resulted in the publication of maps for the areas indicated in Fig. 1 and 2

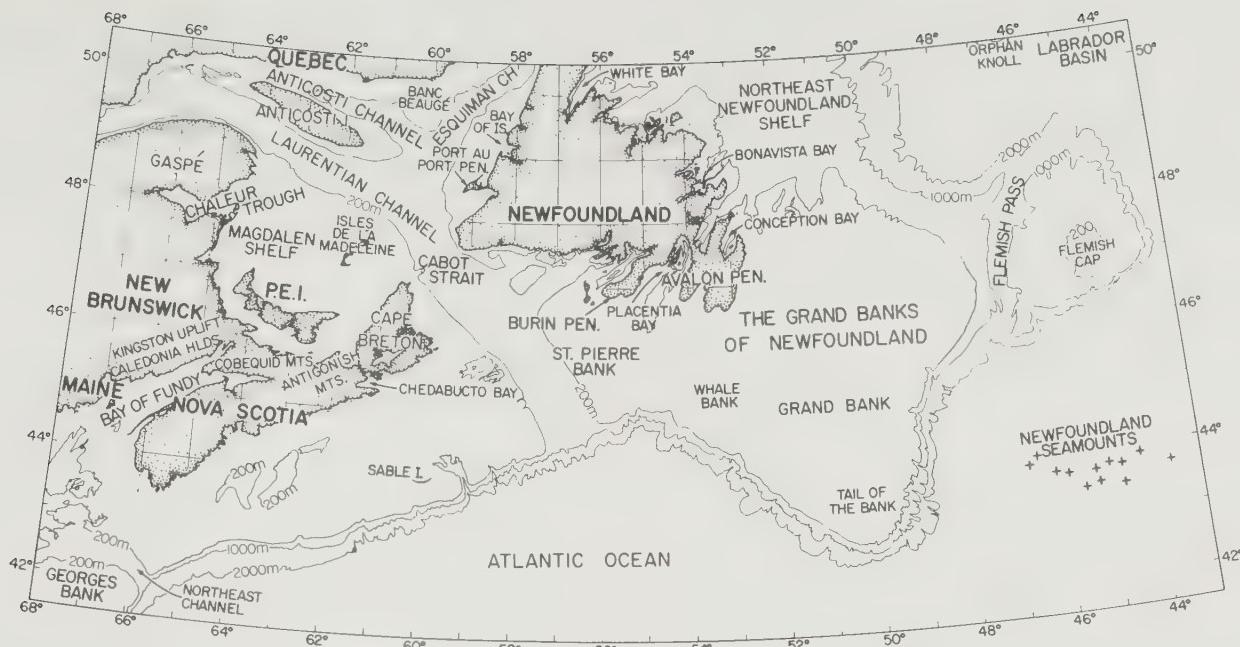


FIG. 4. Physiographic elements of Atlantic Canada and locations referred to in text.

(Canadian Hydrographic Service 1974). Free air gravity anomaly maps for the Gulf of St. Lawrence were not included in the contract because hand-contoured maps prepared from the same data had been published a year earlier in the Natural Resource Map Series. However, the contractor was required to produce 1:1,000,000 compilation sheets of Bouguer and free air gravity anomalies, magnetic total field and magnetic anomaly for all areas of detailed coverage including the Gulf of St. Lawrence. For the Gulf, the published hand-contoured free air anomaly maps were compared with the machine-contoured product and good agreement was found (Haworth and MacIntyre 1975). This indicated that there was little error in the digital file for the Gulf and it has been used with confidence in this compilation. For all other areas for which Natural Resource Series maps have been produced, the substantiation of accuracy is much better because each individual line has been investigated. If the data have been demonstrated to be inaccurate, those data have either been corrected or deleted (Haworth 1974a) and the edited data have been mapped at 1:250,000. The same data have been used for the 1:1,000,000 compilation, the differences in the final presentation due solely to the differences in the grid sizes used. Outside the areas for which Natural Resource maps were produced, the data were collected on more widely spaced lines, and the data were compiled as discussed in Section (3).

2) PUBLISHED CONTOUR MAPS OF DATA FROM OTHER INSTITUTIONS

Geological Survey of Canada (Resource Geophysics and Geochemistry Division)—The Geological Survey of Canada (GSC) has an extensive program of aeromagnetic surveys, having completed coverage of much of central Canada and the Atlantic Provinces (McGrath et al. 1973). In offshore eastern Canada, some sea magnetometer data were also collected, although the areas covered were limited and in

general no indication of track lines is given on the published maps. The basic means of publication of the aeromagnetic data is as maps of the total magnetic field at a scale of 1:63,360 with an overlay of flight lines to indicate control. In general, digital data from the surveys are not available, the original data being primarily in the form of analog records.

The GSC magnetic data have been compiled in the form of magnetic anomalies and presented at a scale of 1:5,000,000 as the Magnetic Anomaly Map of Canada (1971). That map depicts anomalies with respect to a reference field which is a modified version of the map of the total field (F) for 1965.0 (Dawson and Dalgetty 1966). A new compilation is being prepared at a scale of 1:1,000,000, and a copy of a partially completed Maritime Provinces map was kindly made available to the authors by Dr Peter Hood. The new version shows anomalies with respect to IGRF and hence will be compatible with the marine data presented in this report. Far more detail is available for the land coverage than can be obtained from the more widely spaced lines of the marine surveys. Since the authors were primarily concerned with defining a regional field as background to the marine survey data, the Magnetic Anomaly Map of Canada (1971) was used as the basic data source for land coverage. The new 1:1,000,000 map was referred to in places where it could provide better definition of contours of the regional field (primarily in Nova Scotia and New Brunswick) than was available from the Magnetic Anomaly Map of Canada at 1:5,000,000. Since the Magnetic Anomaly Map of Canada is contoured at 200- γ intervals, and a 100- γ contour interval is used for the marine data and the contribution from the new Maritime Provinces map, there is a disruption in the contour levels at the junctions between data sets. Another disruption of contours arises because of the difference between the reference fields to which the various surveys have been referred. No attempt has been made to

adjust the contours of either set of data since such adjustment would have to be arbitrary. When the basic aeromagnetic data are available in digital form, or the new 1:1,000,000 compilation of land data is complete, it should be possible to integrate the data in a more satisfactory manner to provide better continuity between the survey areas. Even now the continuity of contours across the survey boundary in the Gulf of St. Lawrence, for example, is very good.

Some distortion exists in the Magnetic Anomaly Map of Canada (1971). Some anomalies that were observed on BIO surveys close to the north shore of the Gulf of St. Lawrence are not shown in their correct position. Although positioning errors of up to 20 km can be seen in the vicinity of the Quebec North Shore, the authors would have been faced with an overwhelming task in trying to eliminate the distortion over the land areas of the GSC surveys. If users wish to investigate localized correlations of the magnetic field with other parameters in the areas covered by the GSC surveys, they should refer to the basic 1:63,360 total magnetic field maps of the Geological Survey. It is again emphasized that the potential fields used as a background for the marine survey data are intended to show regional aspects only, and cannot be used as a prime data source.

Earth Physics Branch (Gravity Division) — The Gravity Division of the Earth Physics Branch (formerly the Dominion Observatory) is engaged in the regional gravity mapping of Canada. Generally, the data collected are compiled and published in the Gravity Map Series, each map usually having an accompanying report. Longer interpretative texts are also available for some areas. The reports and maps of Weaver (1967, 1968) for Newfoundland, Tanner and Uffen (1960) for Gaspé, Thompson and Garland (1957) for Quebec, Goodacre, Brûlé and Cooper (1969) for the Gulf of St. Lawrence, Garland (1953) for the Maritimes, and Stephens et al. (1971) and Stephens and Cooper (1973) for the Scotian Shelf have been used in the compilation of regional gravity data. These data were collected with a wide variety of instruments, particulars being given in each survey report. All the recent land data in the compilation area have been collected with LaCoste and Romberg gravimeters. The Earth Physics marine surveys were carried out by taking spot measurements on the sea floor with a LaCoste and Romberg gravimeter suspended in gimbals and housed in a watertight case. A regular grid of measurements can be made at sea with relatively few restrictions, for example depth of operation. The Gravity Division has used 13 km (8 miles) as its standard station spacing in order to define the regional gravity field (Goodacre et al. 1969) and much of the underwater gravity data has been collected on such a regular grid. On land there are difficulties with traverses, and much of the earlier data was collected as discrete measurements at points along the road network. Garland (1953) collected his data at 13-km intervals along roads, but since the road system in Nova Scotia is geographically peripheral, there are large areas that have little or no coverage. Weaver (1968) has provided coverage of Newfoundland on a regular grid with the use of helicopters and float-equipped aircraft. The station spacing was generally 10–13 km (Weaver 1967).

Except for the Scotian Shelf and south of Newfoundland, the contours from maps of the Earth Physics gravity surveys have been transferred directly to the compilation presented here to provide the regional gravity field as background for the BIO survey data. For most of the gravity maps this was relatively easy, since scale and projection did not have to be changed. The gravity maps for Newfoundland (Weaver 1968) are at a scale of 1:500,000 and hence the transfer of contours from those maps may not be as accurate.

Gravity data for the Scotian Shelf-Laurentian Channel region could have been presented in either of two ways as both the Earth Physics underwater gravity data and the BIO data were available in digital form. It was possible to use the EPB data either alone with their 13-km ($\frac{1}{8}$ ° of latitude) average station spacing or in combination with the BIO data and present them in the form used for the sparsely covered areas as described in Section (3). The latter course was chosen so that the detail in the gravity and magnetic maps presented in this report would be compatible, and so that there would be no abrupt change at the edge of the continental shelf and at the junction with the Grand Banks at 56°W where the EPB underwater coverage stops. The disruption of the contours is placed at the shoreline where the marine data stops and the sole data source becomes the grid of EPB land data. Although this means a loss in definition in this presentation of some of the gravity anomalies on the Scotian Shelf, that detail may be found in the original publication of the EPB data (Stephens and Cooper 1973).

For a more regional but uniform definition of the gravity field of Atlantic Canada incorporating all the EPB and BIO data by use of a computer gridding technique, the reader may refer to the Gravity Map of Canada (1974).

United States Department of the Interior—Geological Survey (USGS) — The margins of the compilation area include part of Maine. Since the USGS has published gravity and magnetic maps for some of that area, the available data have been included in this compilation. The magnetic contour information was obtained from a map of the Gulf of Maine region (Kane et al. 1972b) because of convenience in scale. Kane et al. (1972b) report that the data on their map were adopted from an aeromagnetic map of the eastern continental margin of the United States (Taylor et al. 1968). The gravity data on U.S. territory used in the present compilation were taken from a Bouguer anomaly map of New England (Kane et al. 1972a), which was compiled from several quoted sources.

3) SPARSE BIO AND OTHER DATA

The poorest comprehensive geophysical coverage of the compilation area exists on the Scotian Shelf and the adjacent continental slope and rise. Apart from a survey of the Orpheus Anomaly (Loncarevic 1964), the data have been collected mainly by BIO ships going to and returning from various survey areas (Bay of Fundy, Mid-Atlantic Ridge, Grand Banks, Gulf of St. Lawrence, Baffin Bay, Caribbean, etc.) during the last decade. Due to this “target of opportunity” type of coverage, the data tend to be somewhat unevenly distributed, with a predominantly E-W line pattern. Over part of the area the gravity data were augmented by bottom gravity

measurements made by the Earth Physics Branch. The resulting distribution of data points is highly variable, with sample concentrations of up to two observations in a 1-km square grading, sometimes rapidly, into only few points or none at all in a 30-km square. Since the data coverage could not uniformly resolve gravity or magnetic features with a wavelength of less than $\frac{1}{4}^{\circ}$ (approximately 28 km), a $\frac{1}{4}^{\circ}$ grid spacing was selected as the basis for machine contouring.

Two basic steps are involved: the production of a regular grid of data to represent the thousands of randomly positioned input data points, and the contouring of that grid. Both steps can be carried out using the California Computer Products Inc. package GPCP (Calcomp 1971), but this approach was rendered impractical by considerations of computer core storage. A maximum of 760 random points per run could have been used to produce a grid and then be contoured using the CDC-3150 computer available. Since 40,000 gravity and magnetic field values were to be processed, it was necessary to reduce the number of data points before input to GPCP. A second program, GRIDIT (Richardson 1969), was used to prepare from the 40,000 random data points, a smaller but representative set of data values on a regular grid for the use of GPCP.

Program GRIDIT prepares a grid of data upon specification of the following input parameters: (1) geographic position of the center of the grid cell at the southwest corner of the area to be processed; (2) the size of each "square" grid cell expressed in degrees of latitude; and (3) the size of the area to be processed expressed as the number of grid cells per row (longitudinal extent) and per column (latitudinal extent).

The program first calculates a value for the ratio of degrees of latitude to degrees of longitude at the mid-latitude of the grid area, in this case 45°N . Using this ratio and the input parameters, the program calculates the coordinates of all grid cells in the area. The arithmetic mean of all (gravity or magnetic) data falling within each grid cell is calculated, and the computed mean values are assigned to the center positions of their respective grid cells. Since the interpolation and grid-filling options of the program were not used, data output consisted of the average value, with its latitude and longitude, for each grid cell not void of data.

GRIDIT could not produce a geometrically square grid. The ratio between the length of a degree of latitude and a degree of longitude used as a constant in the calculation of grid cell boundaries is not constant on a globe. North of the equator the area of a grid cell increases from north to south in any region, the grid cells being square only at the mid-latitude. As the area of the grid cell increases, so does the wavelength of the filter that the gridding scheme effectively introduces. The effect of the difference in area, in this case a maximum of $\pm 5\%$ north or south of the mid-latitude of 45°N , was not considered significant.

Because voids exist in the output from GRIDIT in areas of no data, and because the geometry of the grid produced is not precisely that required by the contouring portion of GPCP, the GRIDIT output was put in to GPCP as "randomly

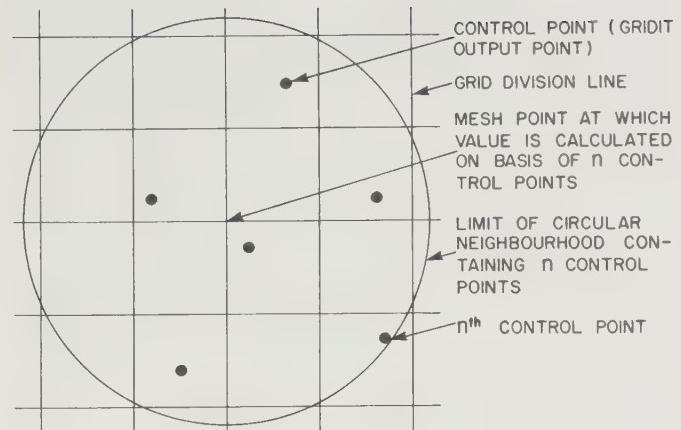


FIG. 5. Definition of terms used in description of the computer contouring system GPCP (Calcomp 1971). See text for details.

distributed" data. This meant that the 760-point limit was applicable, but with $\frac{1}{4}^{\circ}$ GRIDIT grid spacing, the entire area of irregularly spaced data coverage could be contoured in a single computer run.

GPCP operates on all data as (x, y, z) points in a Cartesian coordinate system where x is longitude, y is latitude and z is the value of the parameter measured. At each data point location (each GRIDIT output point) a weighted gradient of the parameter z is calculated based on that point and n surrounding points (Fig. 5). The weighting is inversely proportioned to the square of the distance to the point being considered, and n is user-specified. If the value of n is small, only close points are considered and the gradient calculated is a localized one: there is little smoothing. If n is large, the degree of smoothing is comparatively large. For each (x, y, z) GRIDIT output point, there then exists a calculated gradient.

A grid, which may or may not correspond to the GRIDIT grid size, is then applied to the data as illustrated in Fig. 5. For each GPCP mesh point (grid intersection point), a weighted value for the parameter z is calculated on the basis of the z values and previously calculated gradients at each of the n surrounding data points. These z values on the regular grid are those which are put in to the contour portion of GPCP. With choice of input parameters, the GPCP contours were plotted in a rectangular coordinate system at approximately 1:1,000,000 scale to be compatible with the remainder of the compilation.

The rudimentary gridding scheme used by GRIDIT prior to input to GPCP can inject considerable distortion into the potential fields being contoured. If, for example, only one survey line passes through a grid cell, the calculated average value, positioned as it is at the center of the cell, would effectively shift that section of line out of position by as much as half the grid spacing. This can be significant due to the coarse grid spacing.

It is possible to reduce the distortion created by GRIDIT by the method illustrated in Fig. 6. The dashed square

represents an area within which are located four random data points. The solid line grids in GRIDIT 1-4 represent the positions of the averaging grid in each of the four possible equispaced grid situations. The averaged data value within each grid cell is shifted to the center of the grid cell, i.e., to the head of the arrow shown. For each application of GRIDIT the position of the average value is shifted in such a way as to distort the picture which would have been produced by the random data. In the lower portion of Fig. 6, the numeral 1 represents the position of an average value from GRIDIT 1, 2 from GRIDIT 2, and so on. It can be seen that if all four GRIDIT grids are combined, the composite consists of data on a regular grid (with grid spacing equal to half the GRIDIT

grid spacing) and with each of the random data points represented by a cluster of average values surrounding that point. A contour map from the composite will be more valid spatially than any of the component GRIDIT grids.

To examine the effectiveness of this approach, four $\frac{1}{4}^\circ$ GRIDIT runs were made on the complete set of magnetic field data, each grid being $\frac{1}{8}^\circ$ offset from any of the others. Each of the four resulting GRIDIT grids was contoured by GPCP with minimum smoothing. A comparison of a portion of the four magnetic anomaly contour maps (Fig. 7) shows the relative distortion of localized features due to accidents of grid placement. On combining the four GRIDIT grids and contouring the composite, GPCP produced a description of the field (Fig. 8) that is intermediate to the four separate versions (Fig. 7) and less distorted than any of them. On the basis of many similar comparisons it was decided to use this approach throughout the areas of limited data coverage (Area 2, Fig. 1; Area 3, Fig. 2). Finally it was necessary to redraft the contours using a tilting table to transform the rectangular GPCP plots to the 1:1,000,000 Lambert Conformal conic base maps used in the compilation.

The output of the process described in this section can represent only the strong regional trends of the area. No feature of the magnetic or gravity fields represented with a wavelength of less than twice the gridding interval, approximately 50 km, can be given much credence. This is particularly true for the magnetic field contours which rely only on the widely spaced BIO lines. Some additional help is given to the gravity map by the Earth Physics 13-km grid of underwater data. In using the regional field defined in the areas of sparse data coverage, reference should be made to Fig. 1 to obtain some idea of the control which exists.

INTERPRETATION

The regional patterns of the gravity and magnetic fields of Atlantic Canada (Fig. 9 and 10) markedly reflect the tectonic subdivision of the region (Fig. 11). Discussion of features of the potential fields in this section has been segmented geographically according to the early Paleozoic tectonic subdivision (Fig. 11A). References are made where appropriate to the late Paleozoic trends (Fig. 11B) which may cross older tectonic boundaries.

A more detailed discussion of the potential field trends in the Gulf of St. Lawrence as related to possible Paleozoic continental collision is presented elsewhere (Haworth 1974b).

Limit of Acadian deformation — the southern boundary of the Grenville Orogen — The simplified geological model of Newfoundland is that of two stable Precambrian platforms (the Grenville Orogen and the Avalon Platform) separated by deformed geosynclinal deposits within the so-called Central Mobile Belt (Williams 1964). It has been proposed that the two platforms represent the remnants of continental margins involved in collision as a proto-Atlantic ocean closed (Wilson 1966). The Central Mobile Belt is comprised of the ocean floor and sediment deformed and metamorphosed during collision. Plate tectonics (Morgan 1968) provides a mechanism for

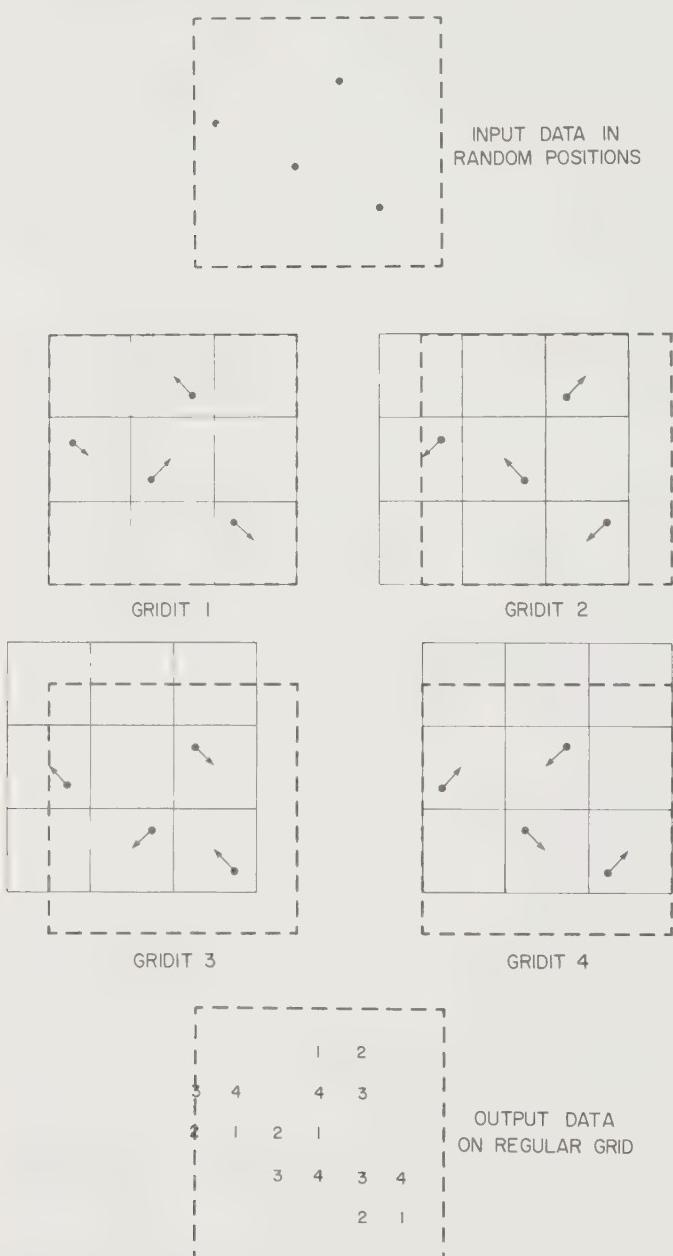


FIG. 6. Preparation of a regular grid of data from random input data by successive use of the program GRIDIT. The output data on a regular grid is the composite of the four symmetrical sets of GRIDIT data shown in the center of the diagram. See text for details.



FIG. 7. Four contour maps of averaged magnetic anomaly produced from the same set of random data. The four regular grids of averaged data were prepared for contouring by use of GRIDIT in the four symmetrical arrangements shown in the center of Fig. 6.

closing the proto-Atlantic, and a regional geological framework from the Appalachians compatible with plate tectonics has been developed (Bird and Dewey 1970).

The northern boundary of the Acadian Geosyncline (Poole 1967; Fig. 11A), of which the Central Mobile Belt is

part, has a strong correlation with changes in character of the potential fields. In Newfoundland the Bouguer anomaly over the Grenville Orogen is approximately 30 mgal less than that over the adjacent portion of the Acadian Geosyncline. Seismic refraction results (Dainty et al. 1966) have shown that

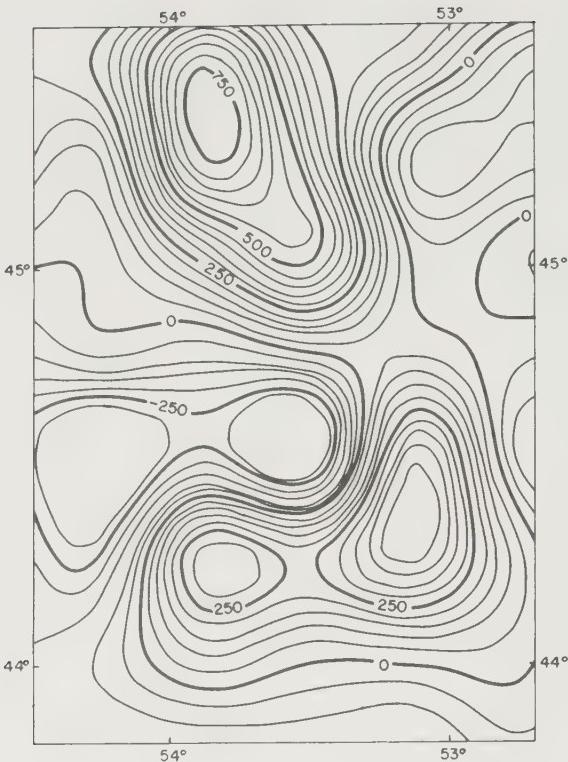


FIG. 8. Magnetic anomaly contour map produced from the composite of the four grids used to prepare the four separate contour maps of Fig. 7. This is an example of the final product of the process illustrated by Fig. 6.

the crust beneath the Central Mobile Belt has a thickness of approximately 45 km compared with only 30 to 40 km under the adjacent platforms. The presence of an intermediate velocity layer within the thicker crust results in the higher gravity values observed over the Central Mobile Belt (Weaver 1967). Because there is a similar increase in the gravity field between the north shore of the St. Lawrence estuary and Gaspé coincident with a thickening of the crust from 35 km (Mereu and Jobidon 1971, 1973; Overton 1973) to 50 km (Rankin et al. 1969), the intermediate velocity layer probably extends beneath Gaspé. The change in level of the gravity field within the Gulf of St. Lawrence is therefore interpreted as defining the northern limit of the thick crust with an intermediate velocity layer, a characteristic of the Acadian Geosyncline. This boundary is the limit of Acadian (Devonian) deformation resulting from continental collision. The localized positive gravity anomalies to be seen at or near this boundary, such as those associated with the Shickshock Mountains of Gaspé (Tanner and Uffen 1960), are attributed to basic rocks intruded at the collision interface. The generally linear gravity high within which they lie may reflect an increase in the density throughout the crustal column due to the upward migration of basic material during orogeny (Innes and Argun-Weston 1967).

A steep magnetic gradient from high values over the edge of the Grenville Orogen to negative values over the Central Mobile Belt is almost exactly coincident with the belt of positive gravity values marking the orogenic front. The oscillatory nature of the magnetic field over the boundary



FIG. 9. Bouguer gravity anomaly trends of Atlantic Canada. The shaded positive and negative areas are approximately 15 mgal greater or less than the regional anomaly. Regional values of the anomalies are particularly difficult to assess near the continental edge where the Bouguer anomaly rises abruptly. Where the indicated trends (--- or +++) link isolated shaded areas, valid continuity is provided by lower values that do not qualify for shading (see full-scale maps).

is similar to the magnetic field over a dipping plate. In this case the plate is represented by the vertical zone of basic intrusives along the orogenic front.

The path of the gravity high and the magnetic gradient are therefore prominent markers of the belt of intrusives. The limit of deformation, north of the intrusives where the crust thins, is more accurately defined by the location of the gravity gradient that is almost coincident with the magnetic high. According to these gravity and magnetic markers the limit of Acadian deformation passes into the St. Lawrence at the northern extremity of Gaspé, thence trending southeast between Anticosti Island and eastern Gaspé (Fig. 12). In the southern Gulf the markers are subdued because of the effect of a thick sedimentary section east of the Magdalen Islands within the Fundy Geosyncline (Fig. 11B). There is however a pronounced change in trend of the orogenic front in the southern Gulf, leading to a landfall in St. George's Bay, south of Port au Port Peninsula. In Newfoundland, the boundary runs northeastward from St. George's Bay to the west side of White Bay, and along the eastern edge of the Great Northern Peninsula (Weaver 1967).

Potential field trends over the Grenville Orogen — North of the orogenic front, the character of the gravity and magnetic field indicates considerable variation in the depth to the Precambrian surface. In Quebec, north of the St. Lawrence, the magnetic field has extremely short wavelength, high amplitude variations resulting from the surface exposure of the Precambrian rocks of the Grenville province. Magnetic field variations generally decrease in amplitude and increase in wavelength with increasing distance seaward from the Quebec North Shore. This generalization is compatible with the increase in thickness of Ordovician and Silurian rocks

observed from seismic refraction data (Fig. 13; Hobson and Overton 1973). The refraction profiles obtained across Anticosti Channel and Esquiman Channel are separated by approximately 100 km. Changes in the gravity and magnetic fields may therefore be used to help refine the basement map based on regional seismic data.

The most pronounced change in the magnetic field occurs in the vicinity of Banc Beaugé, an angular extension into the Gulf at the junction of Anticosti Channel and Esquiman Channel (Fig. 4). The southwest edge of Banc Beaugé is coincident with a steep magnetic gradient (Fig. 10) separating a belt of positive anomalies on the Bank from negative anomalies and a generally smoother magnetic field in Anticosti Channel. This change is not due simply to a change in water depth because the same magnetic feature has another limb which crosses Anticosti Channel without interruption. A less pronounced linear magnetic high trending southeast from Anticosti Island and a magnetic gradient trending from Banc Beaugé towards the southwestern tip of Port au Port Peninsula complete the isolation of a magnetic low. The magnetic low is coincident with a gravity low (Fig. 9) and there is high correlation between even minor variations of the two potential fields. The anomalies may be indicative of a local variation in thickness of the lower Paleozoic sedimentary rocks similar to that inferred from the refraction data west of Bay of Islands, Nfld. (Fig. 13). In that area, the localized increase in depth to the Precambrian surface from 2 km to 4 km (Fig. 13; Hobson and Overton 1973) is coincident with a prominent gravity low (Fig. 9). Weaver (1967) attributed the gravity low to a major granite body extending to a depth of 5 km. However, considering the seismic refraction data, the negative gravity anomaly suggests a greater negative density contrast between the lower Paleozoic rocks and the basement adjacent

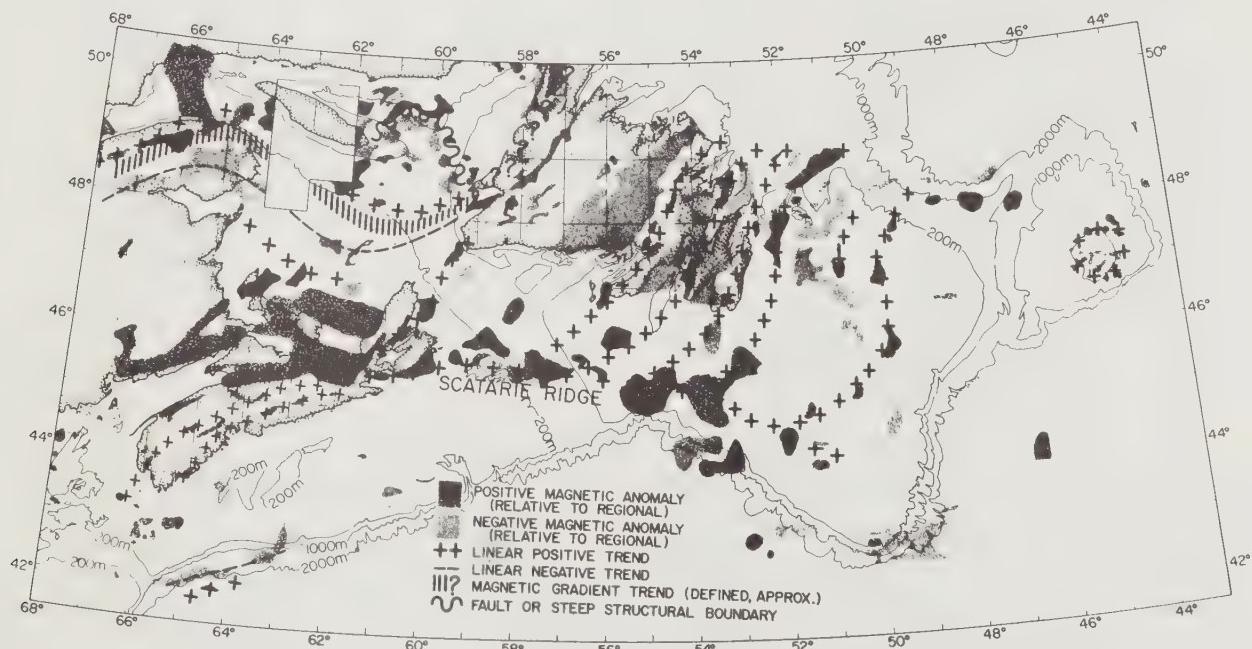


FIG. 10. Magnetic anomaly trends of Atlantic Canada. The shaded positive and negative areas are approximately 200 γ greater or less than the regional anomaly. Where the indicated trends (--- or +++) link isolated shaded areas, valid continuity is provided by lower values that do not qualify for shading (see full-scale maps).

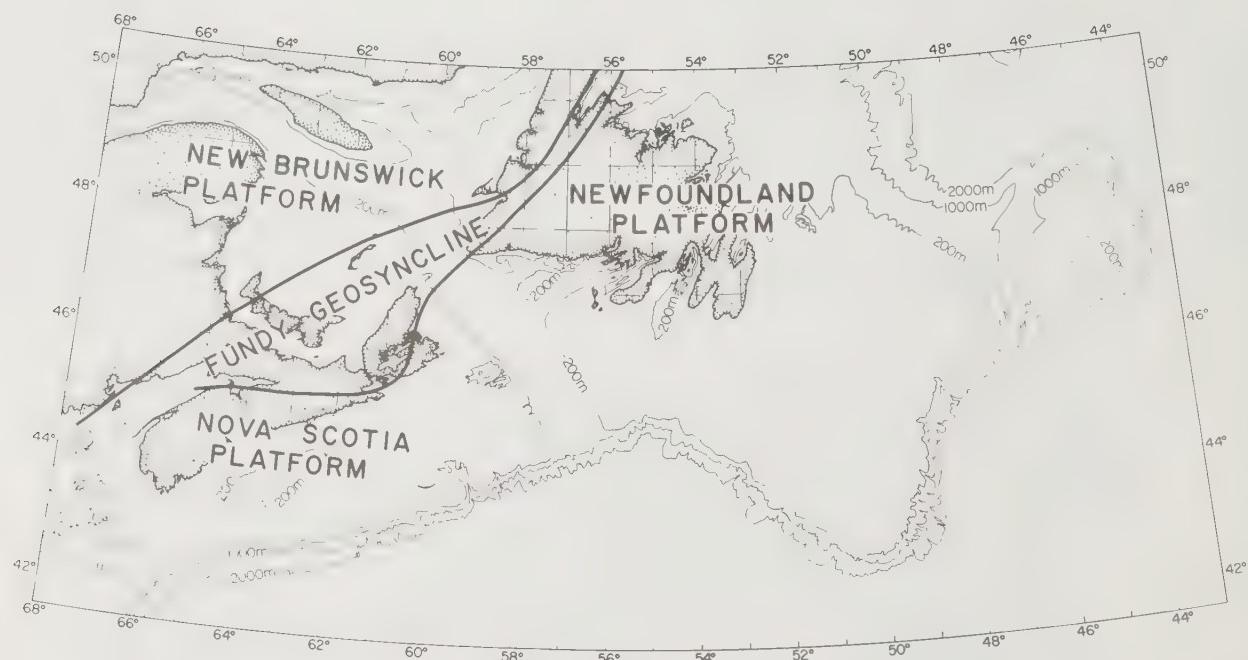
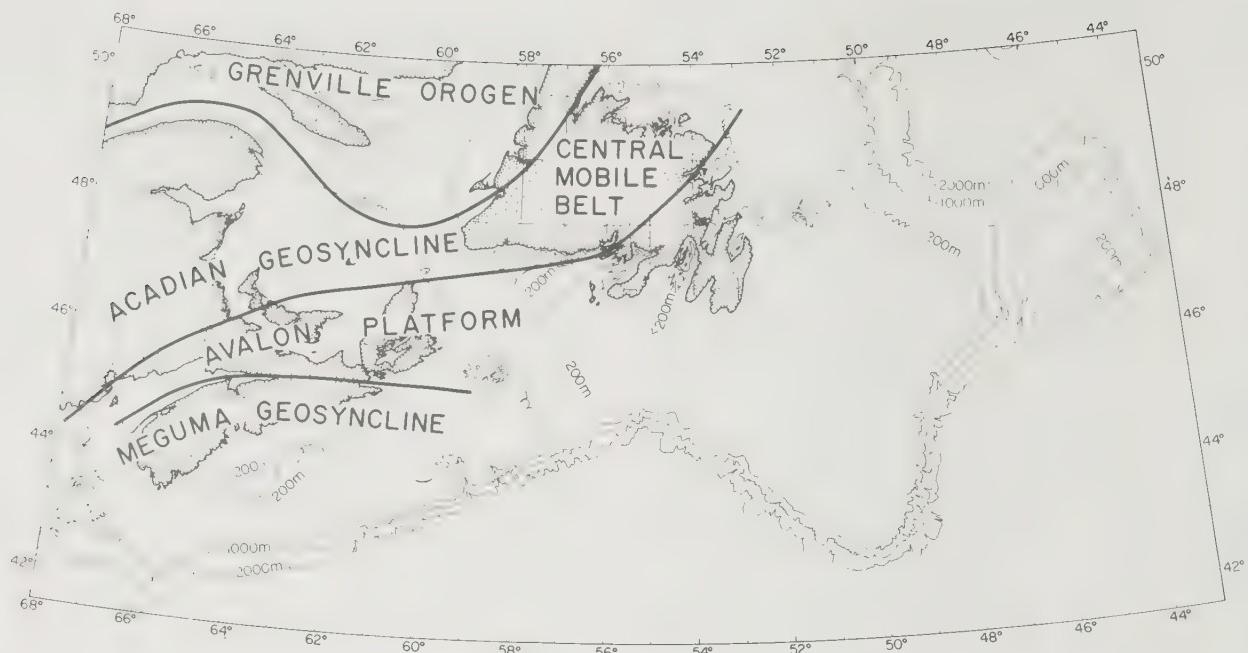


FIG. 11. Tectonic subdivision of Atlantic Canada: *upper*, early Paleozoic (after Poole 1967); *lower*, late Paleozoic (after Poole 1967; Kelley 1970).

to the orogenic front than was observed on Newfoundland (Weaver 1967). The low gravity values over southern Anticosti Island coincide with thickening of the Ordovician and Lower Silurian sedimentary rocks to more than 1.5 km (Roliff 1968), indicating that these rocks also have a negative density contrast with respect to the basement close to the orogenic front. In the case of the Banc Beaugé anomaly, the sedimentary rocks must reach a thickness of 5 km to explain the gravity anomaly, even assuming that they have a negative density contrast with their surroundings of $0.2 \text{ g}\cdot\text{cm}^{-3}$ (Haworth et al. 1975).

This is a high value compared with the density contrast between any of the Precambrian and lower Paleozoic rocks observed on Newfoundland (Weaver 1967). Alternatively, the Banc Beaugé anomalies may be the expression of an anorthosite body at the edge of the Precambrian shield. The geophysical characteristics of the feature are similar to the anorthosite body at $51^{\circ}10'N$, $63^{\circ}30'W$. However, preliminary depth to magnetic basement determinations tend to favor the sedimentary basin explanation for the anomalies (Haworth et al. 1975).

The magnetic gradient from Banc Beaugé to Port au Port Peninsula may represent a regional change in depth to basement. This is probably due to down faulting or down-warping of the Precambrian surface southwest of that line or it may mark the southwestern limit of that basement surface. A ridge of positive magnetic anomalies coincident with a rise in the gravity field trends across the Esquiman Trough towards 50°N , 58°W . This probably delineates a shallow ridge in the Precambrian basement. The gravity field also increases from the Quebec North Shore towards Anticosti Island to give, in Jacques Cartier Passage, a band of high gravity values. This gravity high continues southwestward across the western end of Anticosti Island where the trend coincides with a shallow ridge in the basement determined from aeromagnetic data (Roliff 1968). Each of these examples indicates that there are considerable local variations in the depth to the Precambrian surface throughout the northern Gulf of St. Lawrence, despite the generally gentle southwestern dip ($\frac{1}{2}^{\circ}$ to 2°) of undisturbed Ordovician and Silurian cover rocks observed on Anticosti Island (Bolton 1972) and the general southeasterly dip in the northeastern Gulf deduced from seismic refraction data (Fig. 13).

Since the change in direction of dip of the Paleozoic cover rocks from southeasterly to southwesterly coincides with prominent change in level of the magnetic field extending from

Banc Beaugé to Port au Port Peninsula, that magnetic gradient may represent a significant structural break. It is suggested that the gradient defines a portion of the edge of the North American plate with which the proto-African plate collided in the early Paleozoic. In such a case, extensive faulting of the Precambrian surface might be anticipated, especially at Banc Beaugé near the Precambrian promontory, and either a major intrusive body or extensive sedimentation within the fault system would be expected in that vicinity.

Potential field trends over the Acadian Geosyncline — South of the orogenic front, within New Brunswick, the magnetic and gravity fields are lineated in a general northeast direction following the pre-Carboniferous structural trends. The pre-Carboniferous basement can be approximated to a series of northeasterly striking blocks with varying relative vertical displacements (Bhattacharyya and Raychaudhuri 1967). The Kingston Uplift and the Caledonia Highlands are associated with pronounced gravity and magnetic anomalies due to their volcanic and metasedimentary rocks. Extension of these anomalies towards the Gulf indicates that the structures continue beneath the Carboniferous sedimentary cover (Miller and Garland 1953). Magnetic and gravity anomalies over Miramichi Bay may similarly be caused by faulting within the pre-Carboniferous basement (Howie and Cumming 1967), but McGrath et al. (1973) consider that

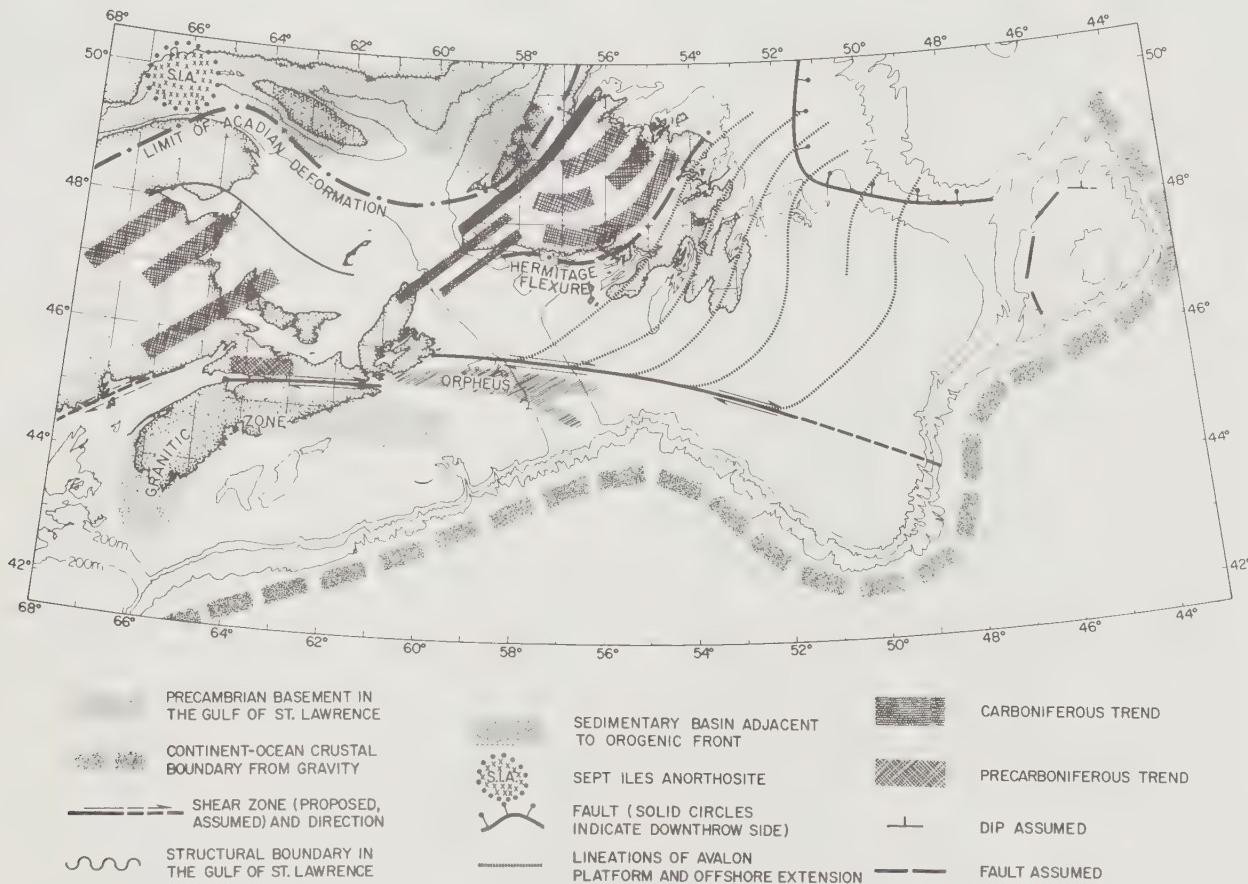


FIG. 12. Summary of structural elements of Atlantic Canada deduced from potential field data.

the anomalies have an intrabasement source. All these northeast trending anomalies are abruptly terminated against a positive magnetic anomaly which is parallel to the orogenic front and which may be part of an "edge effect." The prominent magnetic anomaly at the eastern end of Prince Edward Island may be a continuation of that general positive trend. However, it is likely to be contributed to by complex structures within the pre-Carboniferous basement near the divergence of trends associated with that basement.

The Newfoundland section of the Acadian Geosyncline, referred to as the Central Mobile Belt (Williams 1964), is made up of Ordovician and Silurian rocks that have been extensively folded and faulted. The eastern edge of the Central Mobile Belt is marked by the Hermitage flexure (Williams et al. 1970). Similar flexures of Acadian (Devonian) age and with the same general sense are present throughout central Newfoundland, and are reflected by changes in the magnetic field trends. The marginal unit involved in the Hermitage flexure can be traced offshore to the south of Newfoundland with the help of magnetic profile data and shown to extend eastwards at least 150 km. This supports the contention that the Central Mobile Belt is constricted to a width of approximately 60 km in southwest Newfoundland (Williams et al. 1970).

The fundamental changes in crustal composition and thickness between the Central Mobile Belt and the Grenville Orogen are responsible for gravity values which are predominantly higher in central Newfoundland than on the adjacent stable platform areas. The prominent gravity low in the southwestern part of the Mobile Belt is attributed to a major granite body calculated to be at least 6 km thick at

the center of the low (Weaver 1967). The band of low gravity values at the eastern edge of the Mobile Belt is similarly attributed to the granites. Weaver (1967) calculates that they have a thickness of 3 km in this region and infers that they extend beyond surface exposures, beneath the Ordovician sediments of the Acadian Geosyncline. The Ordovician sediments of the Gander Lake and Baie d'Espoir groups are coincident with the extensive low in the magnetic field of central Newfoundland. The eastern edge of the low marks the eastern edge of the Central Mobile Belt, and that magnetic marker can be used to delineate the continuation of that tectonic boundary across the Northeast Newfoundland Shelf.

The linear pre-Carboniferous trends of New Brunswick are therefore in sharp contrast with the highly flexed trends of Newfoundland. In both cases, however, the trends are abruptly terminated against the southern boundary of the Grenville Orogen. If there is an angular extension of the Grenville out into the Gulf of St. Lawrence as discussed in the previous section, the Newfoundland trends appear to be warped around the edge of that projection while the New Brunswick trends are terminated against its side (Fig. 14). Constriction of the Acadian Geosyncline in southwestern Newfoundland complicates the tracing of any trends which might be continuous between Newfoundland and New Brunswick. Superimposition of anomalies associated with the Fundy Geosyncline tends to make the task impossible.

Fundy Geosyncline — The southern portion of the Fundy epieugeosyncline (Fig. 11B; Belt 1968; Kelley 1970) is bounded on the west by the northeasterly trends of New Brunswick and on the south and east by the east and northeasterly trends of

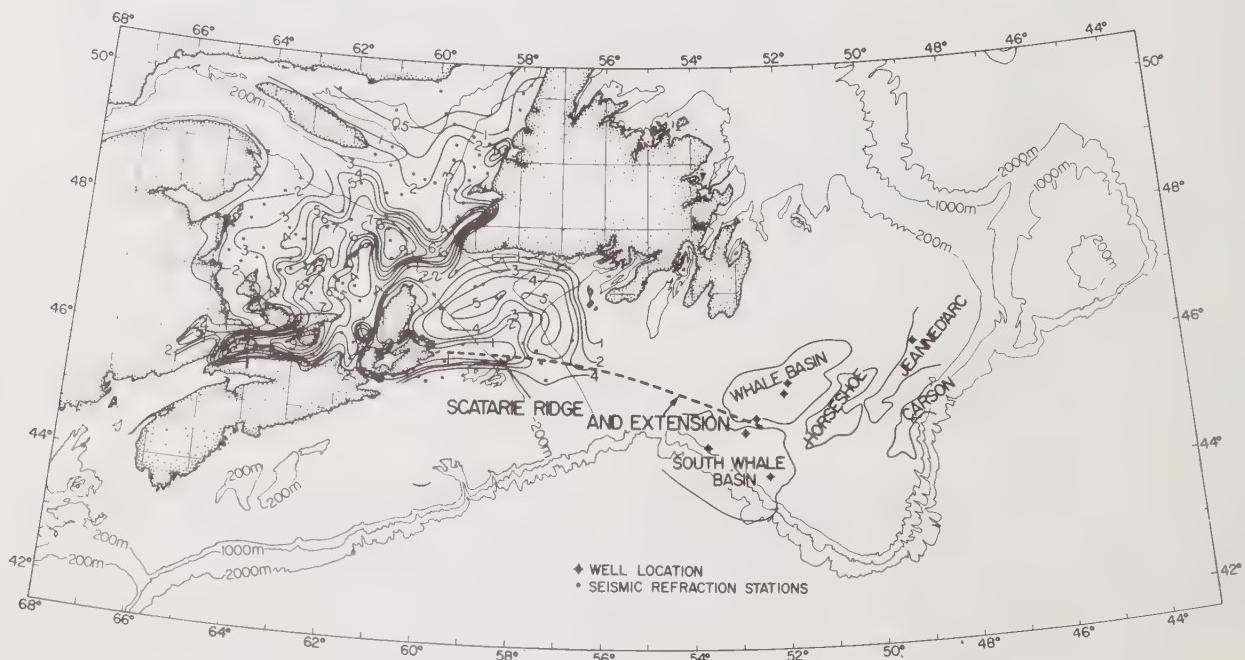


FIG. 13. Basement and sedimentary basin configuration. In the Gulf of St. Lawrence the depths in kilometers to the pre-Carboniferous basement are from Hobson and Overton (1973). East of Cape Breton Island the pre-Carboniferous basement contours are from Sheridan and Drake (1968). The outline of pre-Cretaceous basins on the Grand Banks is taken from Amoco and Imperial (1973).

Nova Scotia. Carboniferous and younger sediments were deposited in a narrow zone bounded by latest Devonian–early Carboniferous faults (Webb 1968). The prominent gravity low between the Magdalen Islands and southwest Newfoundland reflects up to 9 km of Carboniferous sedimentary rocks (Fig. 9; Sheridan and Drake 1968; Hobson and Overton 1973; Watts 1972) within that geosyncline. The sedimentary basin is host to numerous salt diapirs on and to the east of the Magdalen Islands. Those structures can be recognized by local gravity lows (Watts 1972). In Newfoundland the Carboniferous is restricted to a narrow faulted zone at the western edge of the Central Mobile Belt running from the south side of St. George's Bay through Grand Lake out into White Bay (Kelley 1970). The basin is again marked by a relative low in the gravity field. The edge of the northeasterly continuation of the Carboniferous basin is seen on headlands on the eastern side of the Great Northern Peninsula (Baird 1966), but, although the magnetic field is low along a narrow zone which might delineate the basin, the gravity field is high because of the dominating effect of the change in crustal cross section at the orogenic front. The basin does not appear to extend much further than the northern tip of Newfoundland (Sheridan and Drake 1968). The southern extremity of the Fundy Geosyncline appears from surface geology to be extremely complicated (Webb 1968). Little elucidation is obtained from the potential field data. Even the 5-km basin between the Kingston and Caledonia uplifts is not immediately apparent on either the gravity or magnetic maps. Positive gravity and magnetic anomalies correlate with the Triassic North Mountain basalt along the west coast of Nova Scotia, and indicate its offshore extension. The basalt occurs along the eastern edge of the Fundy epieugeosyncline where faults were active in late Triassic (Poole 1967). Seismic profiler data have shown that the Triassic rocks extend out into the Gulf of Maine in a series of troughs separated by Paleozoic basement highs (Uchupi 1966). Magnetic anomalies do not immediately facilitate distinction between these strata, but King and MacLean (1974) have used profiles of the potential field data (Watts and Haworth 1974) in conjunction with seismic reflection information to delineate the bedrock units.

Potential field trends of the Avalon Platform—The Cobequid Mountains of northern Nova Scotia were uplifted during the Upper Carboniferous (Kelley 1970). Prominent magnetic and gravity anomalies reflect their core of metamorphosed pre-Carboniferous sediments. The positive anomalies over the volcanics and metasediments of the Antigonish Highlands are separated from the Cobequid anomalies by lower potential field values over a graben within which were deposited more than 3 km of Carboniferous sediment (Howie and Cumming 1963). The Antigonish anomalies trend north of east and can be continued through the Cape Breton Highlands to southwest Newfoundland. However, the eastward trend established by the Cobequid Mountains is continued by the positive anomalies associated with the Scatarie basement ridge (Fig. 13; King and MacLean 1970) which forms the northern edge of the Orpheus trough (Ewing and Hobson 1966; Loncarevic and Ewing 1967). This eastward band of positive magnetic anomalies marks the southern boundary of the Avalon Platform.

The volcanic rocks in Newfoundland at the western edge of the Avalon Platform produce high magnetic field values which form the most westerly of a series of ridges in the magnetic field striking approximately 025° (Fig. 10), roughly parallel to the geomorphic trends of Avalon Peninsula. These trends are not parallel to those that have been involved in the flexures of central Newfoundland. The Avalon Platform magnetic trends continue southwesterly across the banks and channels south of Newfoundland until they meet the broad band of positive magnetic anomalies trending slightly south of east that is a continuation of the anomaly associated with the Scatarie basement ridge.

Seismic refraction data (Sheridan and Drake 1968) suggest that the Scatarie ridge is composed of pre-Carboniferous metasedimentary and metavolcanic rock. The ridge has 3.5 km of relief and is covered by only 0.5 km of Pennsylvanian-Triassic sediments where it crosses the Laurentian Channel. The pattern of magnetic anomalies indicates that the ridge continues at least to the eastern extremity of the Orpheus Anomaly at 56°W . The two prominent anomalies over Halibut Channel and Whale Bank, and the line of anomalies on the Grand Banks (Fig. 10; Hood 1966) may represent further extension of this feature. Extrapolation of the trend to the eastern Grand Banks would coincide with the location and trend of the Newfoundland Seamounts. None of the anomalies trending south from Newfoundland or south across the Grand Banks cross this lineation. Profiles from individual ship tracks show that the anomalies south of Newfoundland gradually trend more westward with increasing distance from the coast, and tangentially join the Scatarie ridge high or its eastward extension. Because of the way in which the easterly trending feature acts as a “collector” for all features transverse to it, it seems likely that the magnetic anomalies are caused by intrusives along a major shear zone from which emanate the linear anomalies of eastern Newfoundland, possibly marking subsidiary shears (Haworth 1975).

Trends in the gravity field (Fig. 9) follow very closely those of the magnetic field that mark this zone. The exception is in eastern Newfoundland where the gravity field changes are dominated by the effects of granite emplacement and the major change in crustal composition and thickness at the boundary of the Central Mobile Belt. However, the clarity of the gravity and magnetic trends offshore permit good definition of the proposed shear zone which also marks the southern boundary of the Avalon Platform (Fig. 11A and 12).

East and southeast of Newfoundland, the magnetic and gravity anomalies on the Grand Banks trend southwards and then veer southwesterly towards the extension of the Scatarie high. The change in direction occurs along a line trending southeast from St. John's through Virgin Rocks to Carson Canyon. It may be significant that this line is parallel to the southern margin of the Grand Banks. The southwesterly trend is a reflection of the series of grabenlike structural basins mapped on the basis of exploration by Amoco and Imperial Oil on the central Grand Banks (Fig. 13; Amoco and Imperial 1973). The extensive gravity low trending northeast from Whale Deep (250 km south of St. John's) is coincident with Whale Basin, which contains at least 4 km of Jurassic rocks

(Amoco and Imperial 1973). Jeanne d'Arc Basin runs southwestward from the prominent gravity low on the western side of Flemish Pass between 46°N and 47°N. Murre well, drilled at the southern end of that low, demonstrated that over 2 km of Jurassic section was present within the faulted basin and provided the first indication of live oil on the Grand Banks (Amoco and Imperial 1973). South Whale and Carson basins have been identified beneath the edge of the continental shelf. The regional low in the gravity field on the Tail of the Banks may represent another basin within the same structural regime.

On the northern portion of the Grand Bank, north of the St. John's-Carson Canyon line, the two major linear magnetic and gravity anomalies (Fig. 9 and 10) trend northwards and then veer gradually to the northeast. The more prominent of the magnetic anomalies can be traced from Whale Bank, along the outer portion of the Avalon Channel to a point about 40 km east of St. John's where it begins to veer to the northeast. The whole anomaly has a flexed S-shape. Northwest of the northern portion of that anomaly and subparallel to it (in the northwest corner of the marine survey area), a second band of positive magnetic anomalies can be traced onto the Avalon Peninsula through Conception Bay. That band correlates onshore with the Hadrynian(?) volcanics of the Harbour Main Group (McCartney et al. 1966). Farther to the west another subparallel band of positive magnetic anomalies correlates with the Hadrynian(?) volcanics of the Love Cove Group.

The volcanics may mark the boundaries between faulted basement blocks. However, it has been suggested that the Harbour Main and Love Cove groups were produced within belts of island volcanism in late Precambrian time (Hughes and Bruckner 1971, 1972; Frith and Poole 1972). The terrestrial Avalon Platform was interpreted as having been built up as a series of island arcs at the western edge of the craton which later collided with North America. Late Precambrian samples from the Virgin Rocks area (Lilly 1966) and Flemish Cap (Pelletier 1971) indicate considerable eastward extension of the Avalon Platform. It is therefore possible that the linear bands of magnetic anomalies on the northwest Grand Banks (and their correlative positive gravity anomalies) represent island volcanic complexes which formed in the same period as those proposed for the Avalon Peninsula by Hughes and Bruckner (1971). The arcuate shape of the northern portion of the magnetic anomalies may be the direct expression of the ancient island arcs. A flat plate being subducted on a spherical earth will have an arcuate subduction zone with the convex side towards the ocean (Frank 1968). The radius of curvature of the arc depends upon the angle of subduction. In this case the radius of curvature corresponds to a dip of approximately 5°, much smaller than presently observed in the western Pacific and approached only by the dip of plates off Peru and Chile (Isacks and Molnar 1971). For more reasonable inclinations of subduction zones, the radius of curvature of the northern portion of the anomaly must have been less than that observed today, and must therefore have been reduced by subsequent tectonic modification. The cause of that deformation may also have been responsible for the reverse curvature of the southern

portion of the anomaly. The whole area from the eastern edge of the Central Mobile Belt to at least the center of the Grand Banks at 49°W and extending from the southern edge of the Grand Banks to the Northeast Newfoundland Shelf, an area 500 km wide and 600 km long, seems to have been involved in a massive flexure.

East of St. John's, at 47½°N, 50½°W, there is an area of rough bottom topography which is uncharacteristic of its surroundings and which has prominent positive gravity and magnetic anomalies associated with it. The anomalies suggest the presence of an intrusive body or an uplifted basement block similar to that of which Virgin Rocks and Eastern Shoals are exposures, which would then provide erosional contrast with its surroundings. However, preliminary depth to magnetic basement calculations on the feature yield a minimum depth of approximately 3 km. Also, the only other area of comparable relief northeast of St. John's has a gravity low associated with it. The reason for the anomalies and the complex topography therefore remains unknown.

All the features referred to in this section form part of what is now continental crust. Defining the northern edge of that crust is a difficult task which requires more than the superficial analysis presented here. The southern margin of the Grand Banks displays a sharp increase in Bouguer gravity anomaly to more than 200 mgal, which is characteristic of an abrupt change from thick continental to thin oceanic crust. In contrast, on the northern margin of the Grand Banks, although there is a sharp gradient in the Bouguer anomaly between depths of 200 m and 300 m, the terminal value is only approximately 100 mgal (Fig. 9). Anomalies greater than 200 mgal are only seen south of Orphan Knoll in nearly 3000 m of water. In the intervening area the bathymetry gradually increases, but does not appear to bear the simple relationship to the changes in Bouguer anomaly that would be expected if this were a simple bathymetric effect.

The linear magnetic anomalies on the northern portion of the Grand Banks veer northeastwards transverse to the increase in Bouguer anomaly (Fig. 9 and 10). They cross that gravity gradient in the northeast corner of the marine survey area and then, although still continuing, appear to be reduced in amplitude. Unpublished data (cruise *Minna* 73-019) from north of the compilation limits indicate that the magnetic anomalies extending out of Bonavista Bay also cross the extension of the gravity gradient, but are reduced in amplitude at that boundary. Since those magnetic anomalies have their origin in continental crust, that crust must extend beyond the Bouguer gravity gradient into deeper water. It is suggested that the inshore Bouguer gravity gradient (in 200–300 m of water) marks a line along which the continental crust has fractured, the outer portion of the crust having subsided (Grant 1972). The subsided portion of continental crust may extend out to Orphan Knoll at the edge of the Labrador Basin (Fig. 12).

General subsidence along the entire continental margin of eastern North America has been described by Keen and Keen (1973). In particular, analysis of JOIDES drill cores on Orphan Knoll (Ruffman and van Hinte 1973) demonstrates

that Orphan Knoll is a continental fragment which subsided rapidly in the earliest Tertiary. Either such a fragment was rifted to its present position and the intervening old oceanic crust deeply buried, or the entire area out to Orphan Knoll is continental and has subsided much as Orphan Knoll did. The gravity and magnetic data presented here seem to support the second explanation, which was also preferred by Ruffman and van Hinte (1973) on the basis of the absence of transform faults and characteristic continental margin magnetic anomalies.

If the area between Newfoundland and Orphan Knoll is founded continent, secondary effects might be observed at the edge of the founded block. Three gravity highs are situated just seaward of the NW-SE line of gravity gradient (Fig. 9) that may define the inshore edge of that block. The most intense high occurs at 48°N , $48\frac{1}{2}^{\circ}\text{W}$. The amplitude of the anomaly is difficult to assess because of the regional gradient against which it lies, but it is approximately 90 mgal. Since the high gravity values appear to be coincident with a thick sedimentary section observed from seismic reflection data, the positive anomalies may be produced in a similar way to those produced by downwarping of the lithosphere under large sedimentary loads (Walcott 1972). The wavelengths of the anomalies seem shorter than one would expect from previously calculated lithospheric models (Walcott 1972). However, if the continental crust founded along a fracture line, the change in depth to the lithosphere would be more abrupt over the fracture line than if the crust were simply downwarped. The wavelength of the resultant potential field anomalies would therefore be reduced. If this explanation for the positive gravity anomalies is correct, there is a very deep sedimentary trough, or series of basins, running parallel to the northeast margin of the Grand Bank with its axis approximately coincident with the 200 m contour. That trough is transverse to the linear magnetic anomalies trending north to northeast across the Grand Bank, and is coincident with a series of positive magnetic anomalies, some of which may represent intrusions at the crustal fracture. If the positive gravity anomalies were due to sedimentary loading, they would fall between the magnetic highs which are expressions of basement topographic highs: they do.

Qualitative examination of the potential field data therefore suggests that northeast of Newfoundland there is a large area of founded continental crust at the inshore edge of which lies a deep sedimentary trough. However, calculation of isostatic gravity anomalies, examination of the variation of Bouguer anomalies with depth, and detailed correlation of the magnetic and gravity fields must be carried out before this interpretation carries much weight. That work is in progress (R. A. Folinsbee, Atlantic Geoscience Centre, personal communication).

To the east of the Grand Bank, Flemish Cap is also continental, having yielded a granodiorite core with an age of approximately 600 m.y. (Pelletier 1971). Grant (1973) has suggested that Flemish Cap was a portion of the former east Atlantic continental margin. The northern margin of the Cap has a gentle bathymetric slope compared with that of the

southern edge. The corona of high frequency magnetic anomalies delineates the area with a shallow Precambrian bedrock surface. However, the Bouguer gravity anomaly increases radially from a point about 50 km to the north suggesting that the geometrical center of the continental fragment is there, rather than coincident with the shallowest point. Subsidence of the northern portion and subsequent sedimentary accumulation may then account for the observed characteristics. Flemish Pass, which separates the Cap from the Grand Bank, has a band of high Bouguer gravity anomalies associated with it. The highest values occur on the eastern edge of the Pass where they are coincident with high magnetic anomalies and a buried basement ridge seen on seismic reflection profiles (Grant 1973). Between that ridge and the center of Flemish Cap is an area of relatively low gravity and magnetic field which delineates a sedimentary basin formed behind the shelter of the ridge (Grant 1973). The regional high associated with Flemish Pass has values similar to those seen in the anomalous area seaward of the inner gravity gradient northeast of Newfoundland. Flemish Pass might therefore also be the result of subsidence of the continental crust. The conclusion from this might be that Flemish Cap is a simple continuation of the Grand Banks, but it has a markedly different magnetic character. Perhaps Flemish Cap is not part of the Avalon Platform tectonic element, although their ages are similar (Pelletier 1971). The boundary between the two provinces may then have been a line of weakness which was reactivated and led to crustal subsidence.

Potential field trends over the Meguma Geosyncline—The positive magnetic field lineation running from the Cobequid Mountains, through Chedabucto Bay, along the Scatarie ridge, over Whale Bank, and tentatively towards the Newfoundland Seamounts (?) separates the Avalon Platform trends of Newfoundland and the Grand Banks from the very different character of mainland Nova Scotia, the Scotian Shelf, and adjacent areas.

Two large negative gravity anomalies (Fig. 9) dominate southern Nova Scotia and the central Scotian Shelf. The onshore feature can be correlated with a major Devonian granite intrusion (Garland 1953) and the offshore anomaly has also been interpreted as caused by a granite body (Stephens et al. 1971). The negative gravity anomaly caused by the sedimentary rocks of the Orpheus trough, which trends eastward from Chedabucto Bay, is separated from the negative anomaly over the granite of Middle Bank by an E-W linear positive gravity anomaly. This anomaly has been explained as a regional gravity high over the metasediments of the Meguma Group (King and MacLean 1970) or a southern ridge similar to the Scatarie high (Stephens et al. 1971). The absence of high magnetic anomalies makes the former interpretation more tenable. South of the Devonian granites, the gravity field rises quickly to give the generally high positive values generally observed at continental margins. The only major variation from this pattern is the gravity low that extends across the continental shelf south of Yarmouth, N.S. (Fig. 9). This has been interpreted as another granitic intrusion (Watts 1974), completing an arcuate belt of intrusives veering northeast to east through Nova Scotia and across the Scotian Shelf.

Northeasterly trending bands of positive magnetic anomaly throughout southern Nova Scotia mark pyrrhotite-rich zones within the Meguma (McGrath et al. 1973). These bands terminate abruptly against the Devonian granite in central Nova Scotia as outlined by the gravity low. North of the granite, they continue until they are truncated against the Cobequid magnetic high. Those lineations closer to the Atlantic are deviated until, southwest of Chedabucto Bay, they run due east parallel to the Cobequid-Chedabucto magnetic lineament. Aeromagnetic data south of Yarmouth show a pronounced N-S lineation which Bower (1962) interprets as a continuation of the mainland trends within the Meguma. Magnetic lineations in the Meguma therefore change direction from north to east between southern Nova Scotia and Chedabucto Bay. This may be either an indication of an arcuate pattern inherent in the mode of deposition of sediment within the Meguma Geosyncline, or an indication that the sedimentary rocks were flexed similarly to those of the Acadian Geosyncline. If the Meguma Geosyncline has been flexed, the deformation is less than that observed in central Newfoundland. It may be significant that the group of granite intrusions tend to form a band which is also flexed in the same sense, except that the radius of curvature for the granite belt seems smaller.

At the southeast end of Northeast Channel, Gulf of Maine, a magnetic low trends northeastwards (Fig. 10). This linear feature is the landward part of the magnetic edge anomaly at the junction between oceanic and continental crust. The associated positive anomaly can be seen slightly seaward. The edge anomaly can be seen on profiles all along the edge of the Scotian Shelf (Hood 1966) but because of the averaged data used in this compilation it is not distinct. If there is a comparable edge anomaly feature on the Tail of the Banks, it can be seen only at the extreme southeast edge of the detailed data coverage where a positive linear anomaly parallels the shelf edge in a similar depth of water.

HYPOTHESIS FOR THE REGIONAL TECTONIC PATTERN

Continental collision hypotheses by Bird and Dewey (1970) and Schenk (1971) provide a general framework within which many of the features of the potential field of the area may be explained.

Evidence has been presented for an angular extension of the Precambrian into the Gulf of St. Lawrence (Fig. 12). Crude model experiments with wet sand (Haworth 1975) have been carried out to show that simple compression of oceanic sediments against an angular margin can produce the flexure pattern observed in the Gulf of St. Lawrence and central Newfoundland (Fig. 14). In the lee of the projection, trends within the oceanic sediments (New Brunswick) are terminated abruptly against a thrust zone which is warped around the edge of the step (central Gulf of St. Lawrence). The trends of the oceanic sediments colliding with the projected part of the Grenville are warped around the edge of the projection (central Newfoundland). As the compression from the ocean increased, the model demonstrated gravity

sliding of overthrust sediments on the Grenville promontory. This may be equivalent to the development of klippe in western Newfoundland. If the force producing compression has a component parallel to the edge of the Grenville (Fig. 15), transcurrent faults develop in the model during the late stages of compression. These may be equivalent to the Carboniferous faults of the Fundy epeugeosyncline. When the oceanic sediments have been fully compressed, the continental cratons begin having to absorb more of the deformation. Although no attempt was made to be rigorous in modelling rheological parameters, in some models the colliding continental block fractured in a line which approximated the direction of the total vector motion of that margin. This might be equivalent to the Cobequid-Chedabucto-Scatarie fault system. A simple model therefore seems to explain the gross structural features of the Atlantic Provinces and the Gulf of St. Lawrence.

The model becomes more complicated to produce an explanation for the development of the Meguma Geosyncline and the Avalon Platform. Since it has been proposed that the Scatarie magnetic anomaly and its eastward extension across the Grand Bank lie at the southern boundary of the Avalon Platform, and since the area to the south has moved a considerable distance westward (Webb 1968), the Meguma Geosyncline appears to have behaved as a single unit completely distinct from the Grand Banks. This lends support to Schenk's (1971) consideration of continental drift of Nova Scotia in relative isolation from its surroundings. There is little indication from gravity or magnetic data that any part of the Grand Banks has a character like that of the Meguma.

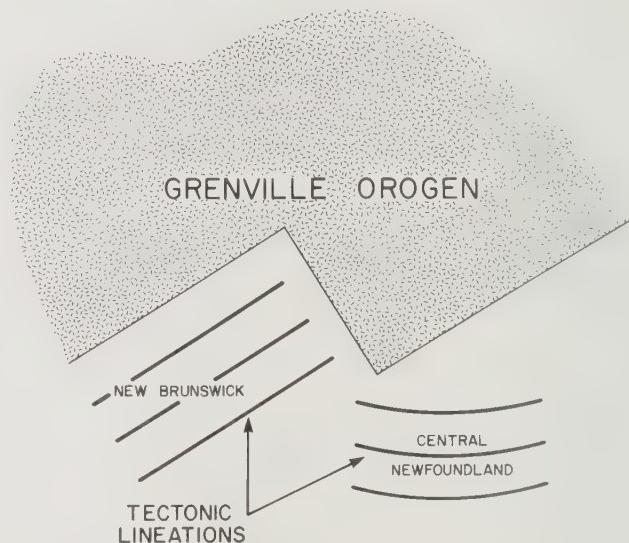


FIG. 14. An angular extension of the Grenville Orogen into the Gulf of St. Lawrence is suggested from seismic refraction and magnetic field data. Pre-Carboniferous trends of New Brunswick are terminated against the side of the promontory, while those of central Newfoundland are warped around its edge.

ACKNOWLEDGMENTS

The inception of combined hydrographic and geophysical surveys, their continuation and expansion, is due to the efforts of Bosko Loncarevic, Russ Melanson, Gerry Ewing, and, more recently, Ron Macnab. However, with any compilation of data there are numerous unsung heroes, in this case the hydrographers and geophysicists who carried out the surveys during which the data were collected. Without the efforts of these anonymous heroes we would not have been able to compile these data, or had such good data to compile.

Having prepared the rough drafts for the maps, we are indebted to the efforts of the Geoscience Mapping group of the Canadian Hydrographic Service for their artistic diligence and technical competence in transforming them into the finished products presented here.

We give our sincere thanks to all these people and to the many interested scientists from whom advice was willingly received.

The manuscript was critically read by Lew King, Bosko Loncarevic, and Ron Macnab, but this does not necessarily imply their endorsement of the concepts it contains.

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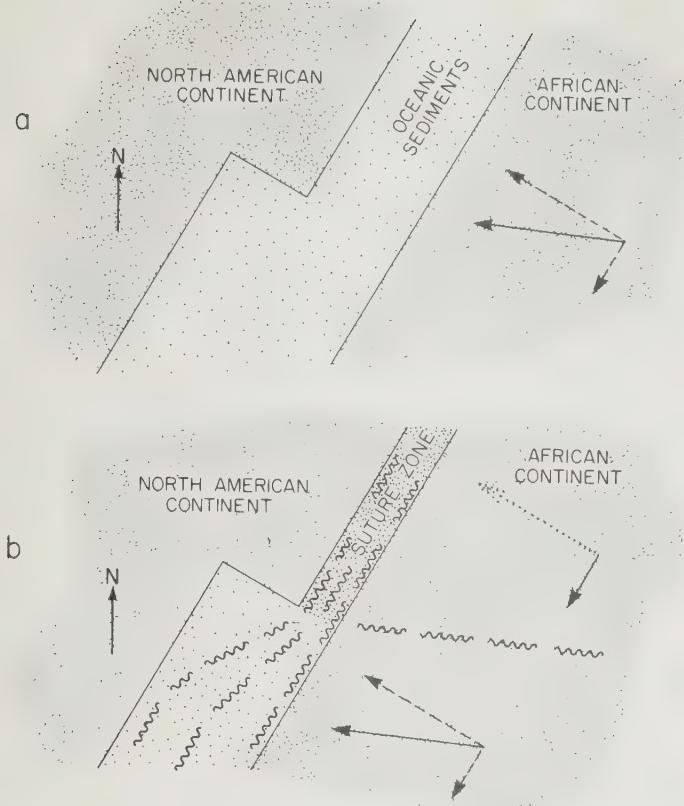


FIG. 15. (a) An "African" continent approaches a "North American" continent with a transverse component of velocity, and compresses the intervening oceanic sediments. (b) When the suture is complete along the promontory the transverse motion produces transcurrent faulting parallel to the colliding margin, and the moment about the edge of the promontory causes the "African" plate to break (Haworth 1975).

The repetitive bands of linear magnetic anomalies on eastern Newfoundland and the Grand Banks suggest that if Hughes and Bruckner (1971) were correct in proposing that the onshore volcanics were laid down as part of an island volcanic sequence, that zone of volcanic activity was very wide. However, it seems more likely that the anomalies mark normal faults developed in the deformed Avalon Platform. From potential field data there does not appear to be any change in general crustal structure from the eastern edge of the Central Mobile Belt to Flemish Pass. Flemish Cap could be a different entity because it has a magnetic character which is distinct from that of the Grand Bank, but this could be due to the greater depths to basement on the Grand Bank masking the detail.

Details of the model studies and the geological support for (and against) this hypothesis are to be found elsewhere (Haworth 1975). The generalities offered here are included merely to supply a unifying concept for the reader to consider while viewing the compilation maps. If the remarks provoke discussion of the maps and draw attention to them, they have served their purpose.

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NEWFOUNDLAND

RIDGE

NEWFOUND

60°

61°

62°

BAY OF FUNDY TO
GULF OF ST. LAWRENCEMAGNETIC
ANOMALYDE LA BAIE DE FUNDY AU
GOLFE SAINT-LAURENT.NORTHWEST
SOUTHEAST

COMPILED BY R.T. HAWORTH, ATLANTIC GEOSCIENCE CENTRE

CARTOGRAPHY BY THE CANADIAN HYDROGRAPHIC SERVICE

BATHYMETRIC CONTOURS IN METRES

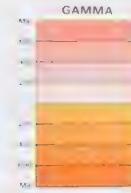
Lambert Conformal Projection (Standard Parallels 43N and 49N)

Scale 1:1000 000

The method used in preparing this map is described in
Marine Science Paper 18, "The Gravity and Magnetic
Fields of Atlantic Offshore Canada" by R.T. Haworth
and J.R. MacIntyre.

Scale of Statute Miles

Echelle de miles terrestres



1. Atlantic Geoscience Centre data averaged over 25 km grid.

2. Moyenne des données du Centre géosciences de l'Atlantique sur un pixel de 25 km.

3. JTS bathymetric survey data in FGCS Quebec 1985 NAD 1950

4. JTS bathymetric survey data in FGCS Quebec 1985 NAD 1950

PUBLISHED BY
THE CANADIAN HYDROGRAPHIC SERVICE
DEPARTMENT OF THE ENVIRONMENT, OTTAWAPUBLIE PAR
LE SERVICE HYDROGRAPHIQUE DU CANADA
MINISTÈRE DE L'ENVIRONNEMENT, OTTAWA

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Imprimé par la Direction des cartes et de la cartographie

Ministère de l'Énergie, des Mines et des Ressources







51°

50°

49°

ROUTE

NEW YORK (101,500)

BAY OF FUNDY TO
GULF OF ST. LAWRENCE
GRAVITY
(BOUGUER ANOMALY)

Compiled by R.T. Haworth, Atlantic Geoscience Centre
Cartography by the Canadian Hydrographic Service

GRAVITY CONTOURS IN MILLIGALS

BATHYMETRIC CONTOURS IN METRES

Lambert Conformal Projection (Parallels 43N and 49N)

Scale 1:1,000,000

Drawing No. 801-D

Series No. 1000

Sheet No. 1

Map No. 1

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NEWFOUNDLAND SHELF
MAGNETIC ANOMALY

Compiled by R.T. Haworth, Atlantic Geoscience Centre
Cartography by the Canadian Hydrographic Service

MAGNETIC CONTOURS IN GAMMA
(Referred to the International Geomagnetic Reference Field)

BATHYMETRIC CONTOURS IN METRES

Lambert Conformal Projection (Standard Parallels 43N and 40N)
Scale 1:1000 000

The method used in preparing this map is described in
Mémoires Scientifiques sur le "The Gravity and Magnetic
Fields of Atlantic Offshore Canada", by R.T. Haworth
and J.B. Macintyre.

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(Anomalies magnétiques reportées au "Système géomagnétique de
référence international")

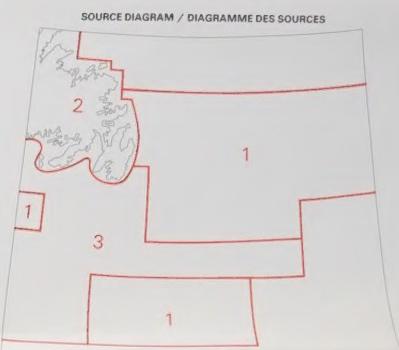
COURBES BATHYMETRIQUES EN MÈTRES

Projection conforme de Lambert (Parallèles standard 43N et 40N)

Échelle 1:1000 000

La méthode utilisée pour la préparation de cette
carte est décrite dans l'étude 16 des Sciences de la
Mer, "The Gravity and Magnetic Fields of Atlantic
Offshore Canada" par R.T. Haworth et J.B. Macintyre.

Scale of Statute Miles
Scale of Kilometres
Echelle de mètres terrestres



1. Données du "Centre géoscientifique de l'Atlantique" et du "Centre hydrographique et océanographique du Service hydrographique du Canada". Les séries de cartes au 1:250 000 et au 1:100 000 ont été produites à partir de ces données.
2. Cartes géologiques du Canada de la Commission géologique du Canada (deuxième édition, 1971) et Geological Survey of Canada unpublished data.
3. Moyenne des données du Centre géoscientifique de l'Atlantique sur un quadrillage de 25 km.

PUBLISHED BY
THE CANADIAN HYDROGRAPHIC SERVICE
DEPARTMENT OF THE ENVIRONMENT, OTTAWA

Printed by Survey and Mapping Branch,
Department of Energy, Mines and Resources

PUBLIÉ PAR
LE SERVICE HYDROGRAPHIQUE DU CANADA
MINISTÈRE DE L'ENVIRONNEMENT, OTTAWA

Imprimé par la Direction des terrains et de la cartographie,
Ministère de l'Énergie, des Mines et des Ressources

MAGNETIC 802-E **MAGNÉTIQUE**
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FIRST EDITION 1974 PREMIÈRE ÉDITION 1974
FIRST BATHYMETRY EDITION 1970 PREMIÈRE ÉDITION BATHYMETRIQUE 1970

